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**FOCAL MECHANISMS FOR
EASTERN CANADIAN EARTHQUAKES:
1 JULY-31 DECEMBER 1998**

**Allison L. Bent
and
Janet Drysdale**

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ABSTRACT

Although earthquake focal mechanism solutions provide information about the faults on which the earthquakes occur and on local stress field orientations and seismotectonics, they have not been routinely determined for eastern Canadian earthquakes. We have attempted to determine focal mechanisms for all eastern Canadian earthquakes of magnitude 4.0 or greater that occurred from 1 July 1998 to 31 December 1998. Ten earthquakes fit the selection criteria. We were able to obtain well-constrained focal mechanisms for three of these events. The seven earthquakes for which solutions could not be determined occurred in the north and offshore regions where seismograph station coverage is poor. In this paper we summarize the solutions and tabulate all data used in their calculation.

RÉSUMÉ

Les mécanismes au foyer des tremblements de terre nous fournissent de l'information sur les failles sur lesquelles les tremblements de terre se produisent, et sur l'orientation des contraintes régionales et séismotectoniques, mais on ne les détermine pas régulièrement dans l'est du Canada. Nous avons essayé de déterminer les mécanismes au foyer pour tous les tremblements de terre qui se sont produits dans l'est du Canada entre le premier juillet 1998 et le 31 décembre 1998 (dix tremblements de terre) et de la magnitude 4,0 ou plus. On a déterminé les mécanismes au foyer pour trois tremblements de terre. On n'a pas pu obtenir des solutions pour sept séismes qui se sont produits dans le nord ou sous l'océan où la couverture du réseau séismographique n'est pas suffisante. Dans cet article, nous faisons sommaire des solutions et fournissons toutes les données que nous avons utilisées pour les déterminer.

INTRODUCTION

Earthquake focal mechanism solutions provide information about the faults on which the earthquakes occur and on local stress field orientations. If focal mechanisms can be determined for many earthquakes in a given region then we also gain insight into regional seismotectonic processes and stress fields. In eastern Canada earthquake focal mechanisms are currently not routinely determined, although solutions may exist for individual earthquakes that were of particular interest as well as for some time periods or regions that have been systematically studied.

We have studied all eastern (roughly defined as east of 110° W) Canadian earthquakes of magnitude 4.0 or greater that occurred during the last six months of 1998 (Figs. 1 and 2). Ten events met the selection criteria. We were able to obtain well constrained focal mechanisms for only three of these events. The remaining seven occurred in the north or offshore where seismograph station coverage is poor. Although we could not determine the focal mechanisms for these events, we were able to place some constraints on the stress axes orientations, and in a few cases, eliminate some focal mechanism types or place rough constraints on the dip of the fault plane. We also include the focal mechanism for an American earthquake that was felt by many people in southern Ontario. Focal mechanisms for events that took place from January through June 1998 may be found in Bent and Perry (1999).

Figure Captions:

- Figure 1.** Map of southeastern Canadian events studied. Symbol size is scaled to magnitude. Magnitude range 4.0-5.4.
- Figure 2.** Map of northeastern Canadian events studied. Symbol size is scaled to magnitude. Magnitude range 4.1-4.4.

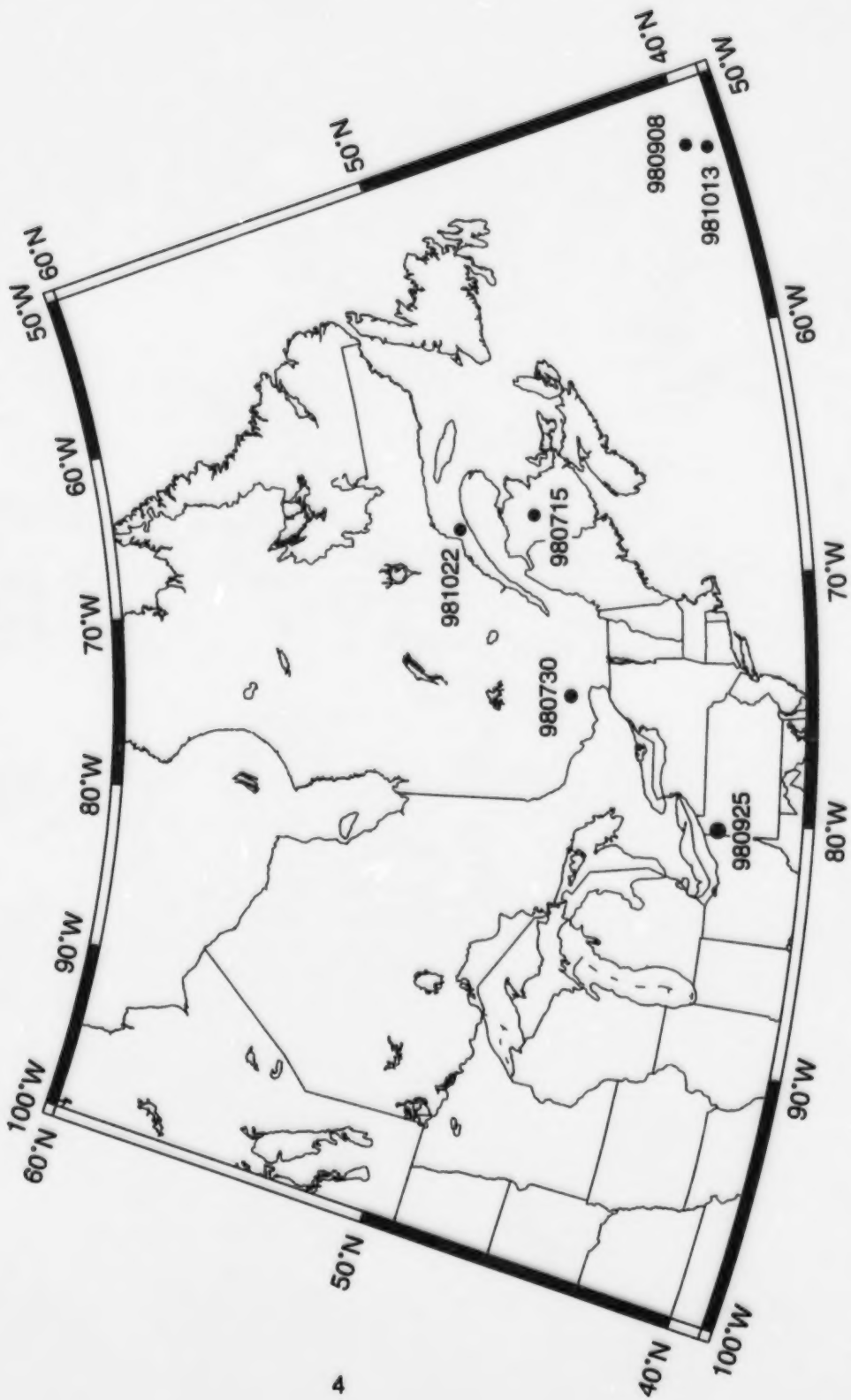


Figure 1

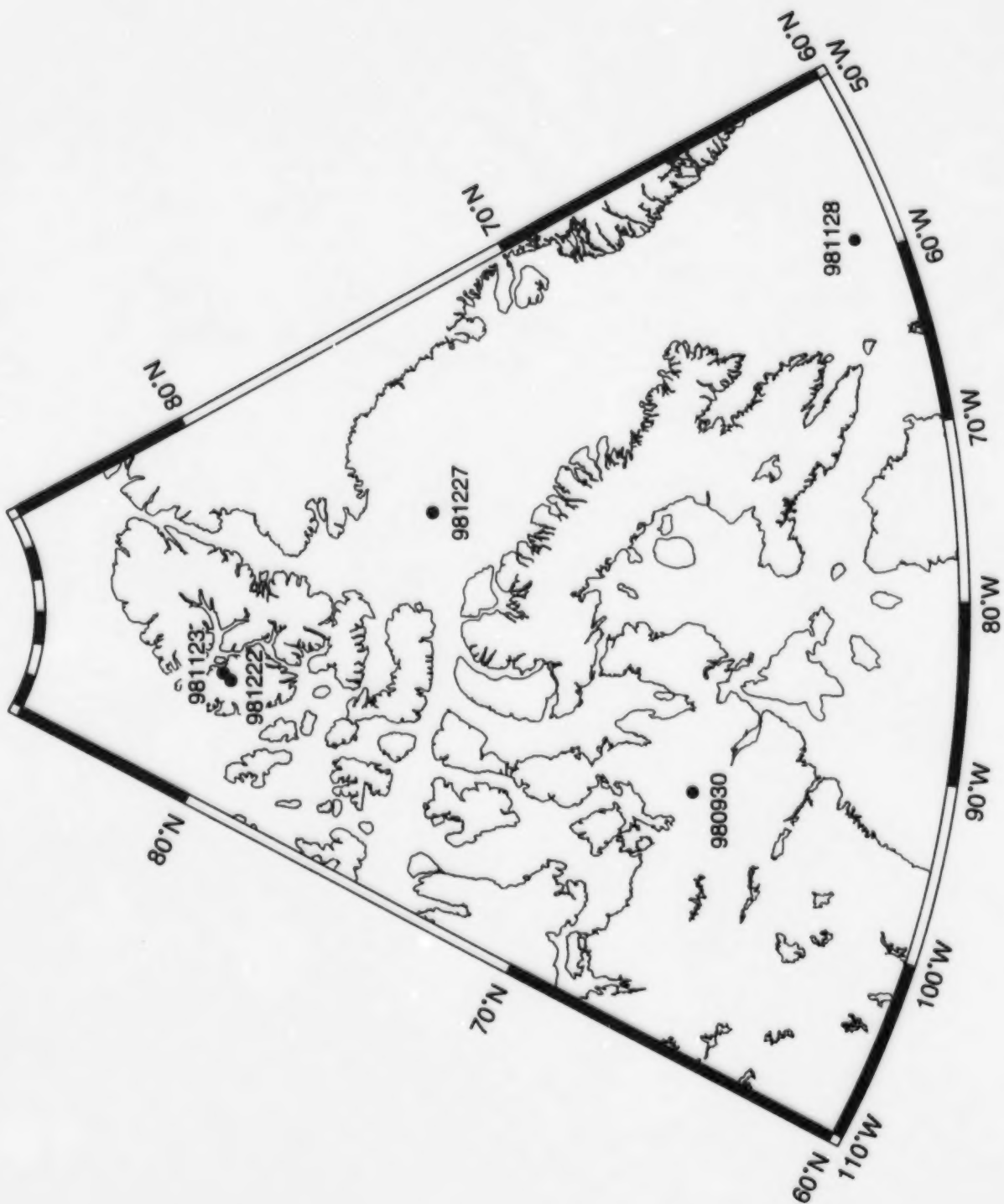


Figure 2

METHOD

The focal mechanisms were determined primarily from P wave first motions. We looked at the vertical component of all digital seismograms contained in the Canadian National Seismogram Network or CNSN (Fig. 3) optical disk archives in Ottawa. Note that data from some western Canadian stations, particularly from the dense array on Vancouver Island, are not routinely archived in Ottawa. However, enough stations from British Columbia are archived that we can determine whether data from the additional stations are likely to be useful, in which case they can be requested. We also included any first motion data contained in the Canadian Earthquake Epicenter File (CEEF) database for which the seismograms were not archived. Generally these polarities were supplied by operators of regional networks or single stations within a few hundred kilometers of the epicenter. In the discussion of individual earthquakes, we note which polarities were not determined by the authors. We attempted to obtain additional seismograms or polarity data if they were likely to better constrain the solution, but did not routinely request external data for southern Canadian events. Similarly, we usually only attempted to read S polarities if the P data did not provide a well-constrained solution. For events in northern Canada, we routinely requested data from two stations operated by the Incorporated Research Institutions for Seismology (IRIS) : Alert (ALE) on Ellesmere Island and Sondre Stromfjord (SFJ) on Greenland. Data from SFJ were also routinely requested for earthquakes in the Labrador Sea. For earthquakes occurring offshore along the southeastern margin, we consulted analog seismograms from stations in Halifax (HAL) and Guysborough, Nova Scotia (GBN) and St. John's, Newfoundland (STJN). Most of the earthquakes we studied were relatively small (magnitude less than 5.0). Therefore we did not routinely attempt to acquire teleseismic data. Non-CNSN stations from which data were used in this study are shown in Figure 4.

First motions were read independently by the two authors. In case of disagreement, the seismograms were re-analyzed and either a consensus was reached or the station in question was not used in determining the focal mechanism.

As much as possible we read the polarities from unfiltered data. However, given that the earthquakes studied were generally small, it was occasionally necessary to filter some seismograms, particularly those from more distant broadband stations. Because high frequencies are attenuated more than low frequencies, there is always some danger that a first motion read from filtered data will not be the true first motion. By restricting the filtering of the broadband data to the frequency range of the short-period instruments (rarely using a corner higher than 1 Hz), we should not adversely affect the data any more than most of instrument responses do. Unless stated otherwise, all filters were two-pole, single-pass Butterworth filters. Any filtering is noted on the seismogram traces where "hp" is used to designate a highpass filter, "lp" a lowpass filter and "bp" a bandpass filter. Corner frequencies are also noted. All filtering of data was performed using the Seismic Analysis Code (SAC) routines (Tapley and Tull, 1991), which were also used to rotate horizontal records into their radial and tangential components.

There was also some concern, particularly for broadband seismograms, that the first motions could be affected by the FIR filters applied to the data. In any case where it was suspected that what appeared to be the first motion was actually a FIR filter artifact, the data were run through a program to deconvolve the FIR filter (Scherbaum and Bouin, 1997). A small apparent first motion followed by a significantly larger arrival of opposite polarity was the principal reason for de-FIR-ring the data. In the end, we found that these small first motions did not appear to be filter related.

As far as we have been able to ascertain the instrument polarities for all CNSN seismograph stations were correct during 1998. The instrument polarities are checked approximately once a year using teleseismic data. Lamontagne (1998) presents the results of a 1997 polarity check for stations in Quebec. The Indian and Pakistani nuclear tests of May 1998 provide further evidence that the polarities of northern Canadian stations are correct (Bent, unpublished data).

The raw seismograms recorded by the CNSN are velocity records. Traditionally first motions have been read from displacement records. We looked at both velocity and displacement seismograms, using SAC to integrate the raw data.

To invert for the focal mechanism, the grid search algorithm of Snoke *et al.* (1984) was used. The search is based on the orientation of the B axis. Normal procedure was to initially search the focal sphere at 5° intervals. If no solutions were found to satisfy all the data, the search increment was gradually decreased. If with a 1° search no solutions were found, we returned to the 5° search, but allowed 1 polarity error. The procedure of alternately decreasing the search interval and increasing the the number of allowed polarity misfits was repeated until at least one solution was found. If the initial 5° no error search resulted in a large number of solutions or if there were large differences among the solutions, we attempted to find more polarity data by reading S wave polarities and/or looking for data from additional seismograph stations. For many of the offshore and northern events, the solutions could not always be further constrained.

Earthquake epicenters were taken from the CEEF. With a few exceptions, depths for eastern Canadian earthquakes are fixed, usually at 18 km (roughly the midpoint of the crust). Only one of the events selected had a calculated depth. Since take-off angle is depth dependent, using an assumed depth will have some influence on the focal mechanism. Having said that, in most cases the effect will be minimal. As long as the hypocenter is within the crust, the take-off angle for Pn and teleseismic P will not be greatly influenced by the depth. At closer distances, the depth will have a greater effect on take-off angle and can also affect the Pg-Pn cross-over distance. However, the close stations are usually few in number, except in the Charlevoix region, where the depths are usually calculated and not fixed, and in any case, it is possible to determine how dependent the solution is on these stations by rerunning the grid search algorithm using the appropriate take-off angles.

Figure Captions:

Figure 3. Map showing the locations of any CNSN stations from which polarity data were used in this project. A complete map of all seismograph stations in Canada (including non-CNSN stations) can be found on the internet. The present site address is:
http://www.seismo.nrcan.gc.ca/cnsn/stn_map_e.html

Figure 4. Map showing the locations of any non-CNSN stations from which polarity data were used in this project.

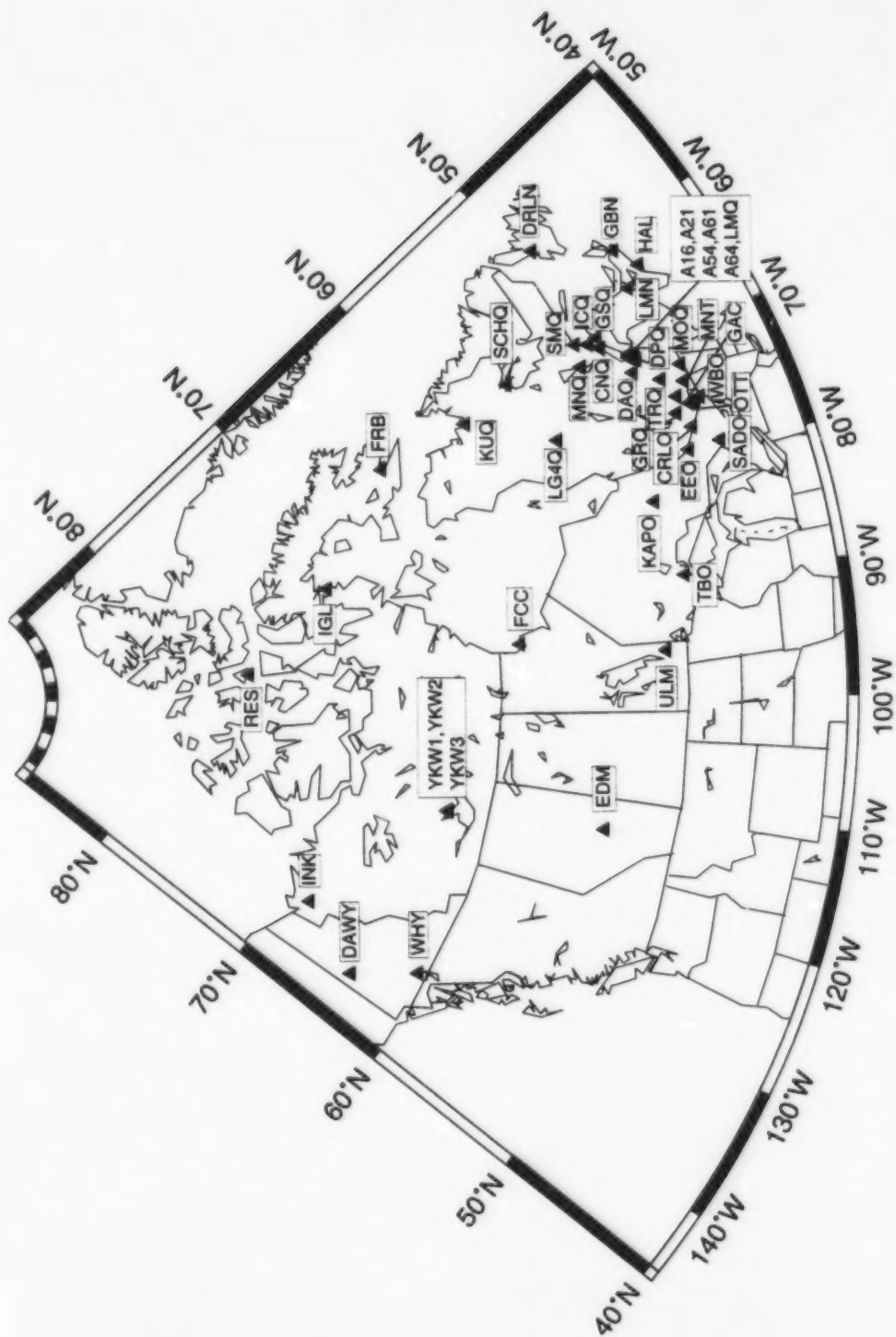


Figure 3

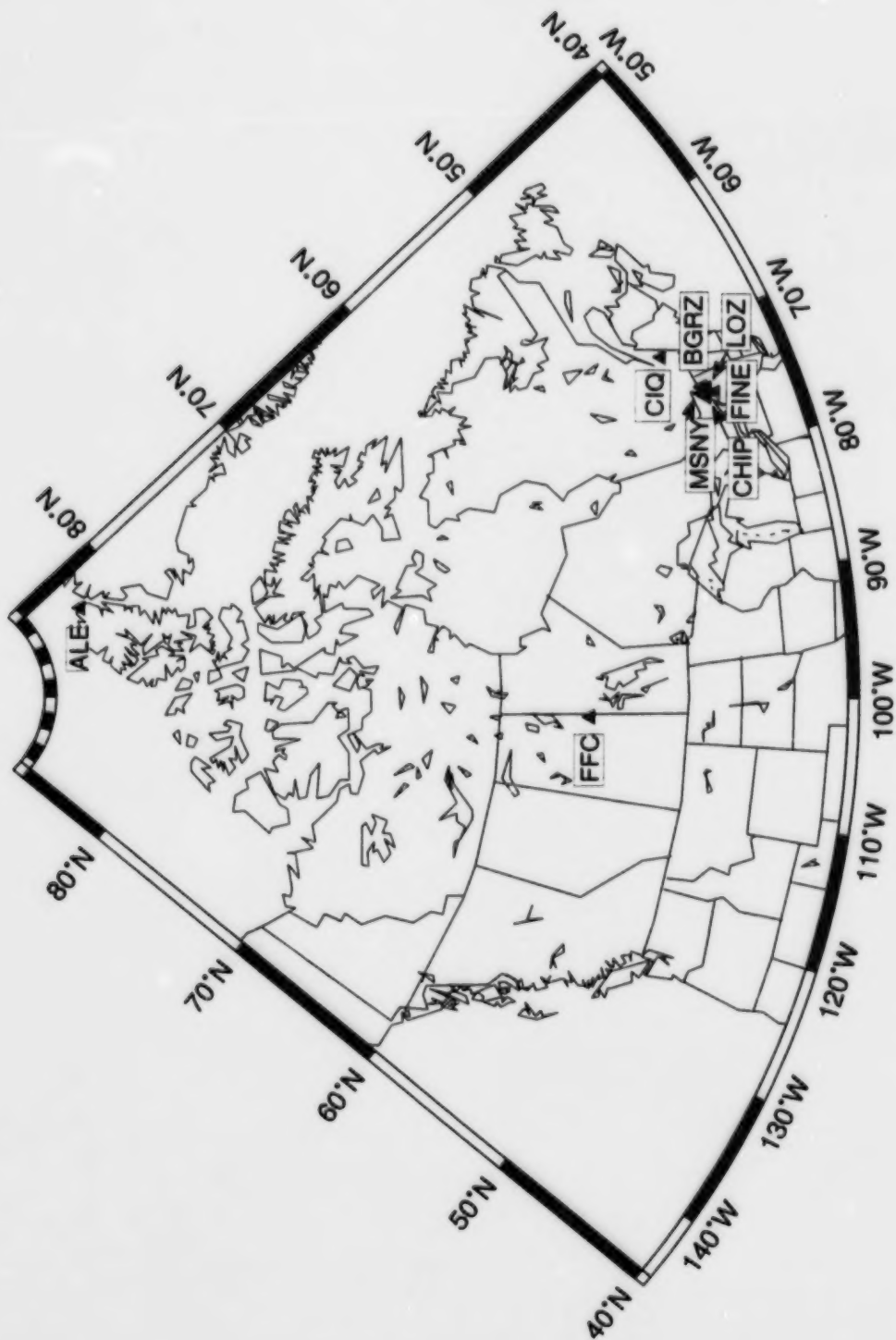


Figure 4

FOCAL MECHANISMS

The epicenters for events included in this study are shown in Figures 1 (southeastern Canada) and 2 (northeastern Canada) and are identified by date of occurrence. For each earthquake, we include a list of polarities used to determine the fault plane solution(s). C's and D's indicate compressional and dilatational P polarities respectively. If the P polarity is emergent, a + indicates compression and a - indicates dilatation. SV waves are indicated by an F for motion toward the station or a B for motion toward the source. For SH waves, a < indicates counterclockwise motion (or to the left if one is facing the station with one's back to the source) and > indicates clockwise motion. Emergent S waves were not used as their polarities are difficult to pick with confidence. We also include portions of all seismograms from which we picked the first motions as well as focal mechanism solutions plotted in terms of both stress axes and P nodal planes.

In the seismogram figures that follow, the velocity records are shown. In an effort to be consistent, we have plotted a constant time window (4 sec) for each seismogram shown. This window is normally adequate to clearly illustrate the first motion, but we note that there may be occasions where showing a longer time segment or the displacement record might have provided stronger evidence for our choice of first motion. Unless explicitly stated otherwise, it should be assumed that any stations close to the epicenter and meeting the criteria discussed in the Methods section that do not appear in the station list for that earthquake were examined by the authors and they could not determine the first motion.

All azimuths and strikes are measured in degrees clockwise from north. Take-off or incidence angles are measured from the vertical. Dip angles are measured from the horizontal. Rake is also known as slip angle. A rake of 0° implies pure left lateral strike-slip motion, 90° pure thrust motion, 180° pure right lateral strike-slip motion, and -90° (or 270°) pure normal faulting. Seismic source zones are as defined by Basham *et al.* (1982). If more than 50 solutions satisfied the data for any earthquake, we do not list them.

Quality rankings of A, B, C or D are associated with each preferred focal mechanism. The quality should be taken not as an indication of how well the solution fits the data but rather as a comment on the quality of the data used to determine the solution. Azimuthal coverage, redundancy of coverage, number of misfits and total number of stations are the principal criteria considered. The availability of S polarity data can help compensate for poor azimuthal coverage as the S and P radiation patterns differ.

Note that at the time of writing the Northwest Territories have been partitioned. We use the term Northwest Territories to represent both the new Northwest Territories and Nunavut as the partitioning had not occurred at the time of the earthquakes studied.

In the Discussion section that follows (beginning on page 82) we try to place the focal mechanisms in a regional context and include a summary table of the solutions.

15 JULY 1998: MIRAMICHI, NEW BRUNSWICK

Seismic Zone: Northern Appalachians
Latitude: 47.02° N
Longitude: 66.61° W
Depth: 5 km (fixed)
Magnitude: 4.0 (m_N)
Origin Time: 07:08:05 (UT)
Comments: felt in New Brunswick

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
LMN	190	132.3	-87.0	D
GSQ	215	350.2	-87.0	D
A21	245	289.3	49.1	C
A16	262	282.3	49.1	D
A64	263	291.1	49.1	C
A61	274	287.3	49.1	+
CNQ	277	337.4	49.1	C
ICQ	283	350.3	49.1	C
LMQ	287	283.3	49.1	-
A54	294	281.1	49.1	-
HAL	354	137.5	49.1	C
SMQ	357	359.0	49.1	C
DAQ	365	288.4	49.1	+
MNQ	423	338.7	49.1	C
GBN	432	112.7	49.1	C
MOQ	475	248.6	49.1	D
MNT	566	255.3	49.1	D
TRQ	615	264.6	49.1	D
WBO	707	254.7	49.1	D

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
GRQ	707	269.7	49.1	-
DRLN	722	66.5	49.1	C
CRLO	833	266.4	49.1	D
SCHQ	870	359.1	49.1	-
LG4Q	908	326.9	49.1	C
EEO	951	272.0	49.1	+
KAPO	1210	288.8	49.1	D

Focal Mechanism Solutions

Strike	Dip	Rake
145.18	55.61	77.85
130.23	67.48	117.23
130.83	66.60	111.88

total number solutions: 3

grid search: 5°

misfits: 0

comments: LMN and GSQ are listed as Pn arrivals in database; using Pn take-off angles, no solutions can be found to fit these stations; first motions at both are clear and records look similar to each other; both stations are near the Pg-Pn cross-over distance; solutions above assume first motions are Pg phases

Preferred solution: use the median solution

Plane 1:

Strike: 131°

Dip: 67°

Rake: 112°

Plane 2:

Strike: 266°

Dip: 32°

Rake: 49°

P-axis:

	Trend:	205°
	Plunge:	19°
T-axis:		
	Trend:	75°
	Plunge:	62°
B-axis:		
	Trend:	302°
	Plunge:	20°
Quality:		B

good azimuthal coverage and redundancy; would have been an A were it not for the question whether LMN and GSQ are Pg or Pn

Figure Captions:

- Figure 5.** Seismograms from which polarity data were read by the authors except for HAL and GBN, which are analog.
- Figure 6.** Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations.

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

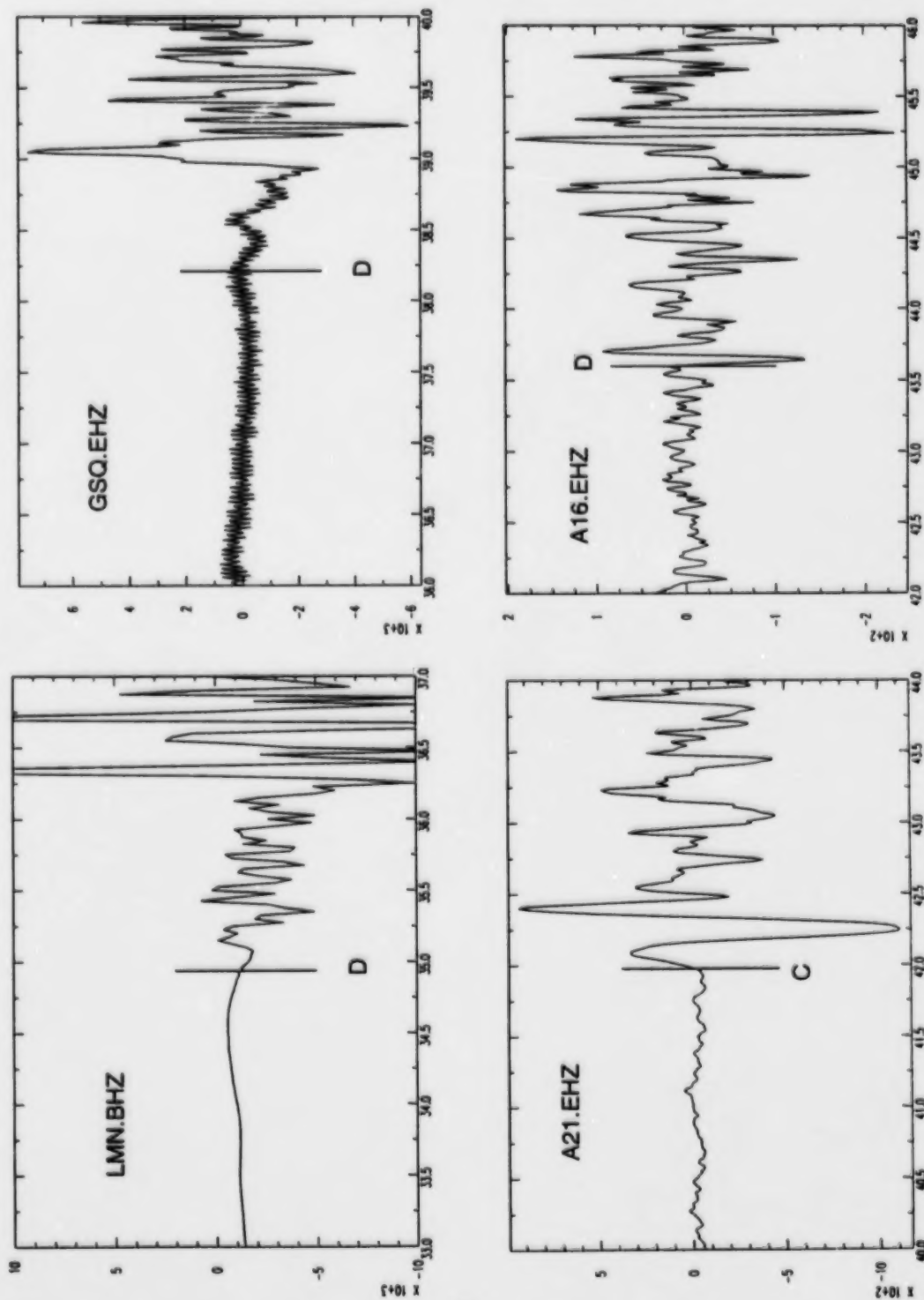


Figure 5a

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

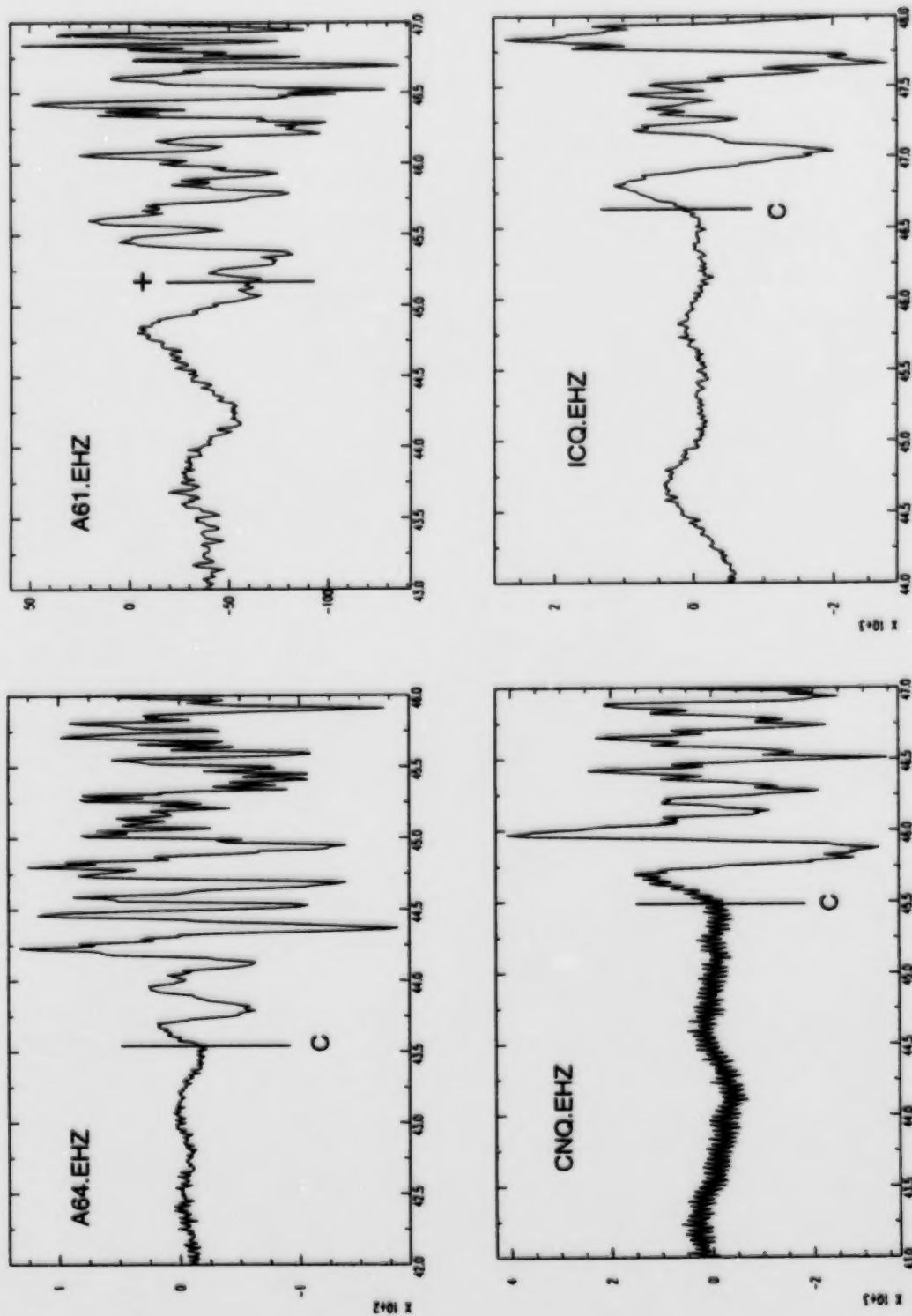


Figure 5b

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

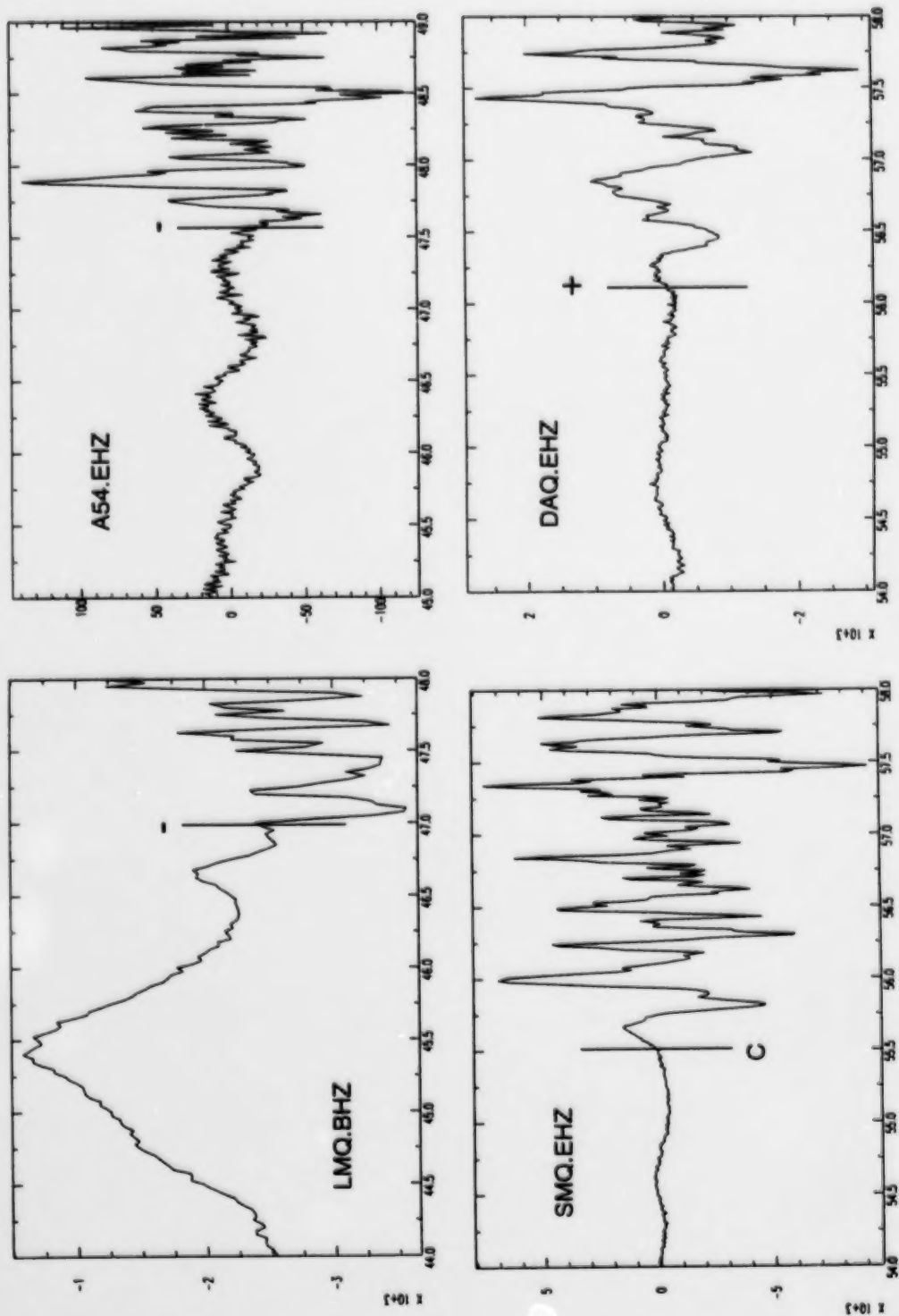
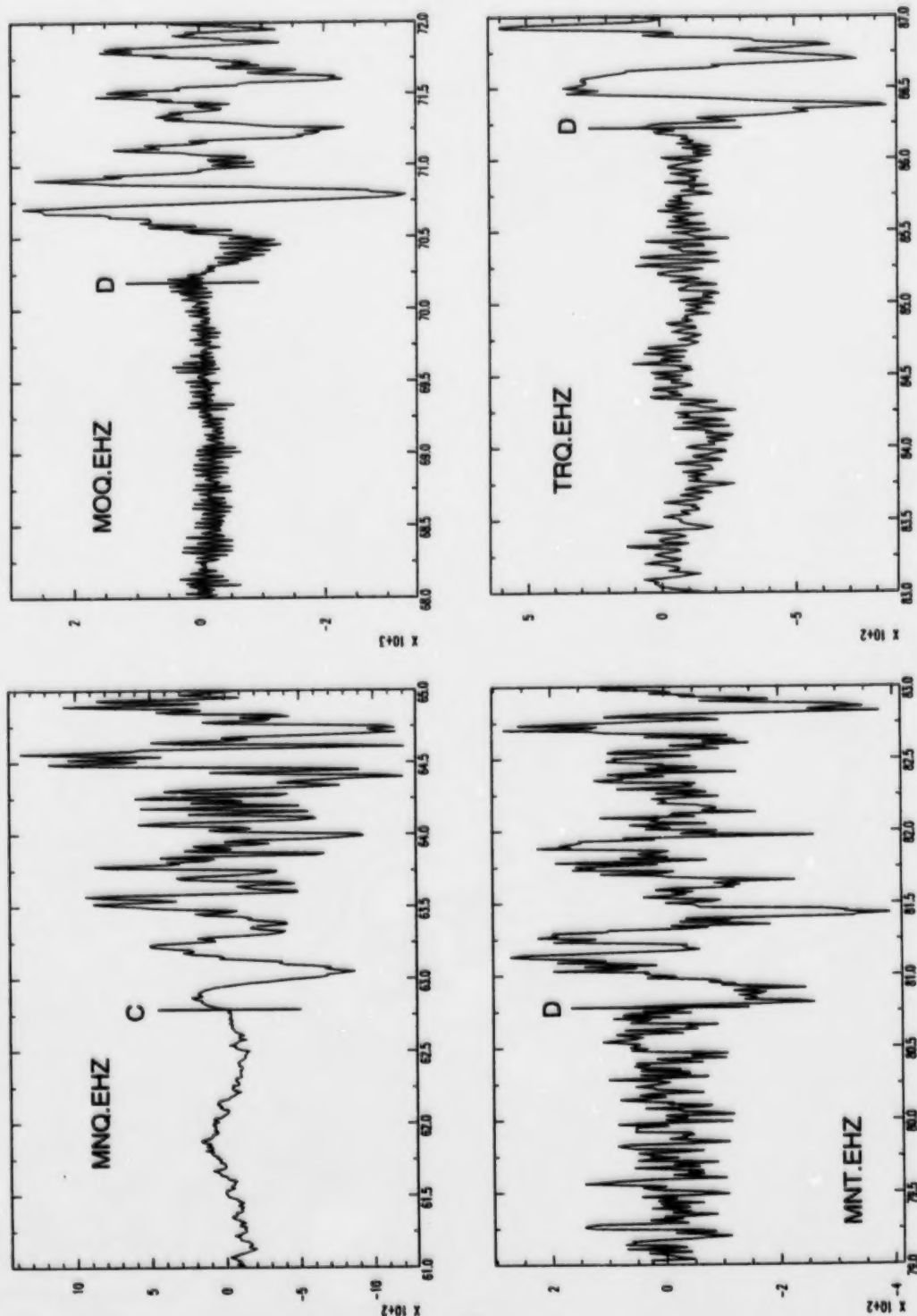


Figure 5c

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998



MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

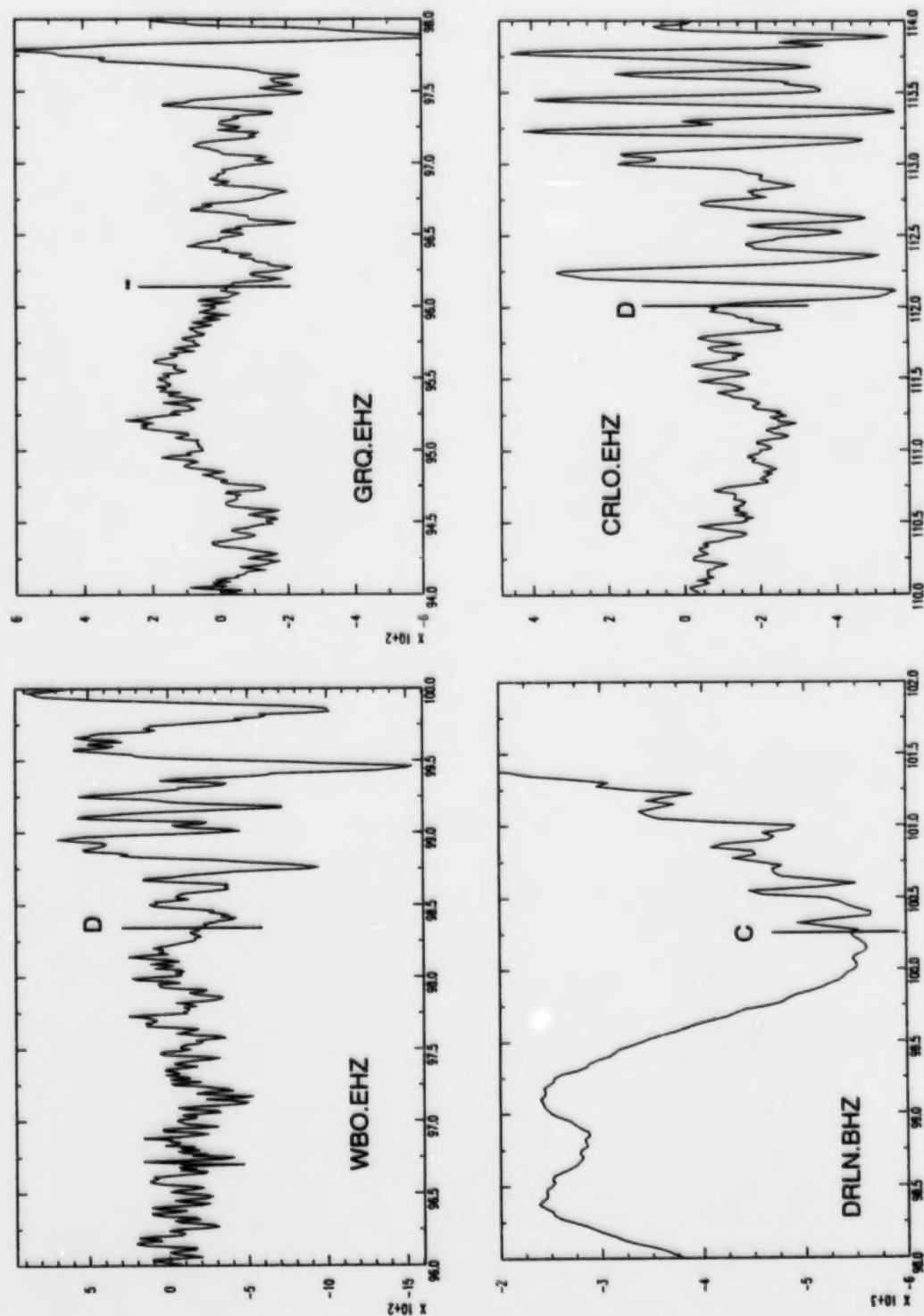


Figure 5a

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

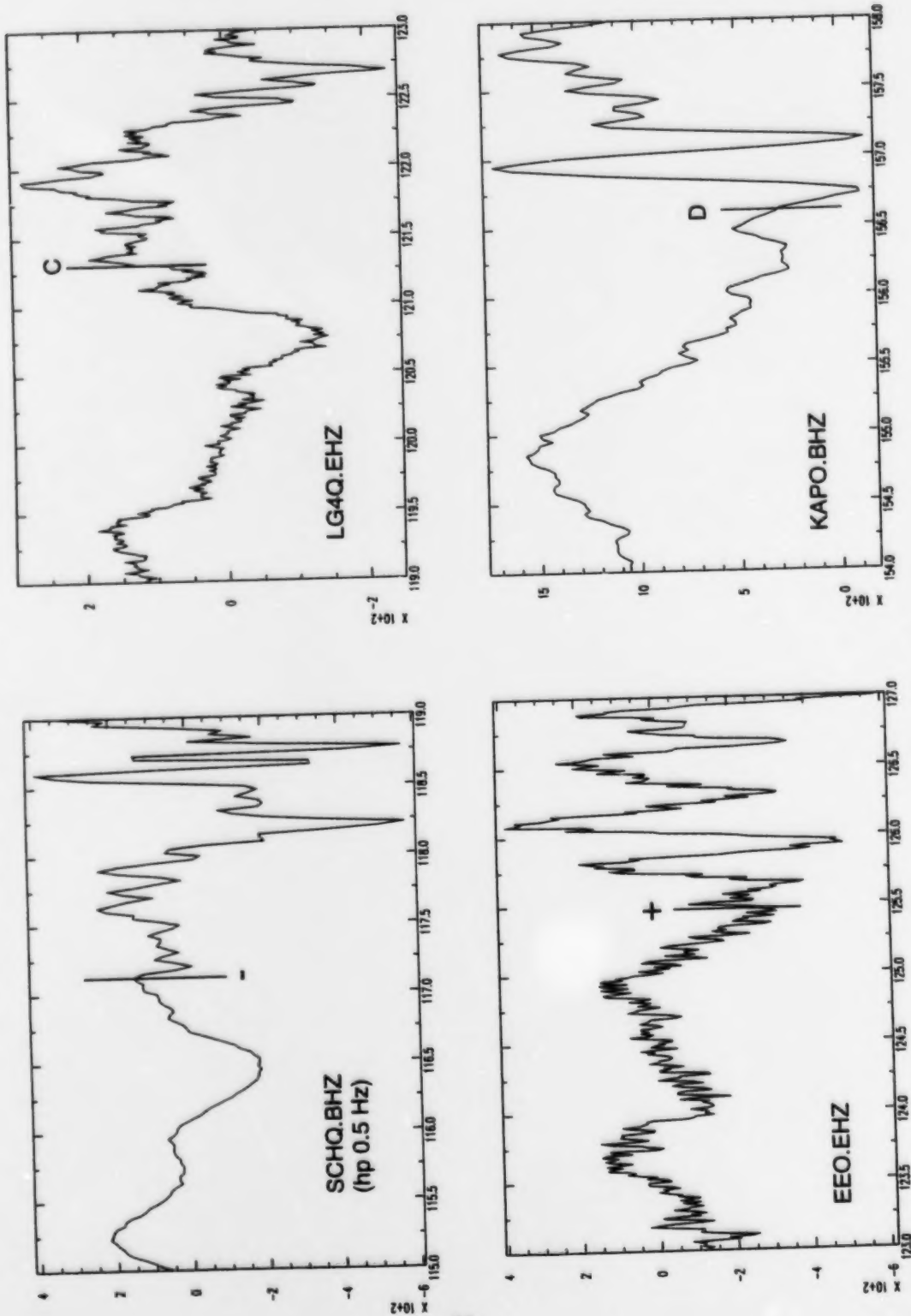


Figure 5f

MIRAMICHI, NEW BRUNSWICK: 15 JULY 1998

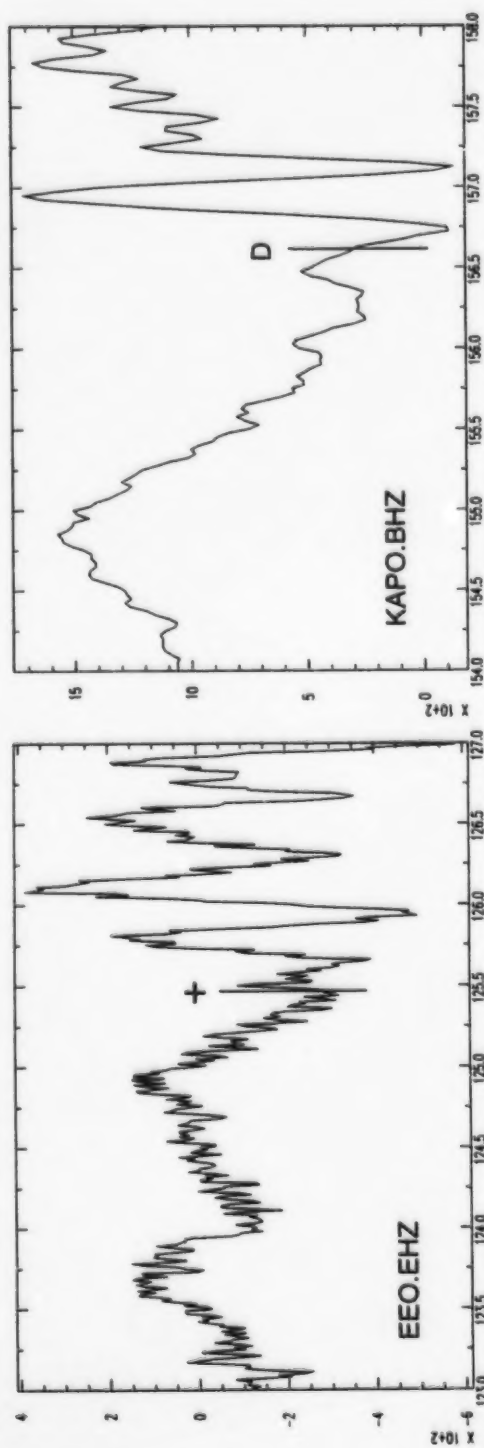


Figure 5g

Miramichi, New Brunswick: 15 July 1998

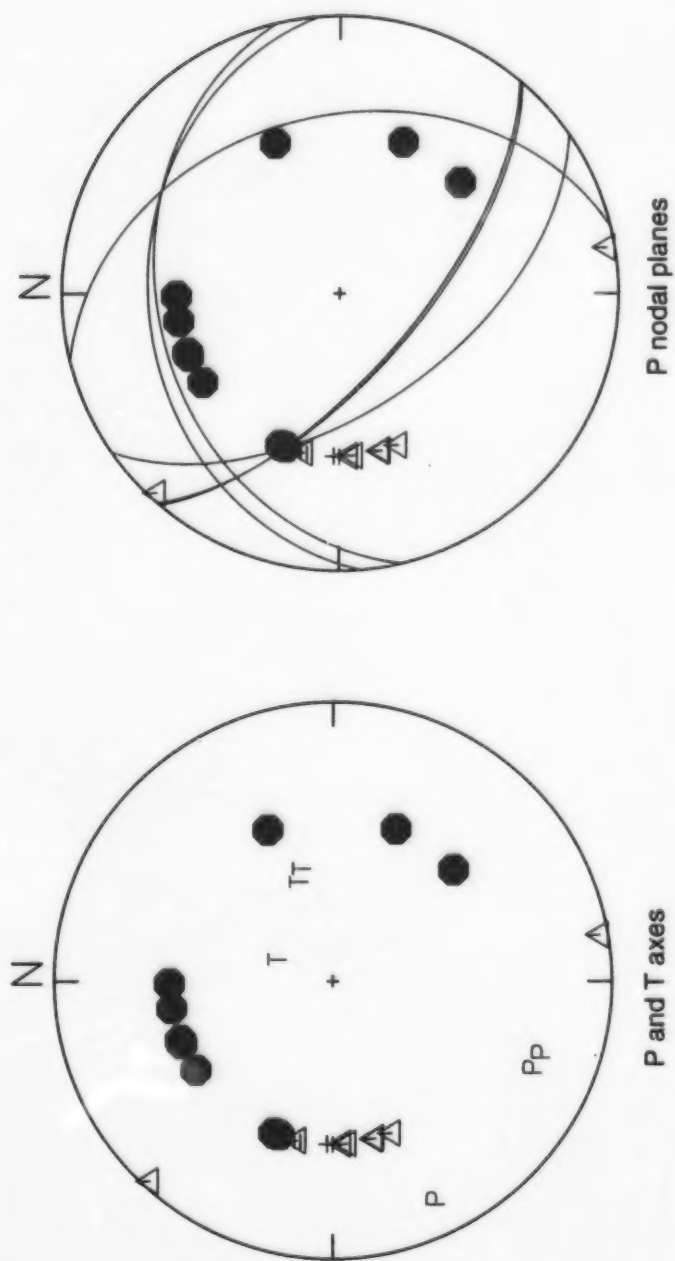


Figure 6

30 JULY 1998: LA CONCEPTION, QUEBEC

Seismic Zone: western Quebec
Latitude: 46.19°N
Longitude: 74.80°W
Depth: 10 km
Magnitude: 4.4 (m_N)
Origin Time: 08:57:22 (UT)
Comments: felt in western Quebec and eastern Ontario

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
TRQ	20	64.7	-56.9	C
GAC	76	229.0	-84.3	D
GRQ	93	299.5	-84.3	D
OTT	114	222.4	-85.0	D
MNT	120	130.6	-84.9	D
MSNY	133	184.5	-85.6	C
WBO	138	198.6	-85.8	D
BGRZ	154	169.2	-86.2	C
CHIP	158	193.5	-86.3	C
LOZ	176	175.9	-86.7	C
CRLO	200	266.9	49.1	C
FINE	216	189.2	-87.3	C
MOQ	221	46.1	49.1	D
EEO	332	280.5	49.1	C
DAQ	335	51.7	49.1	D
A54	364	64.9	49.1	D
LMQ	373	63.8	49.1	D
SADO	374	247.4	49.1	C

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
CIQ	382	50.5	49.1	D
A16	393	61.6	49.1	D
A64	416	61.6	49.1	D
A21	424	64.2	49.1	D
CNQ	612	52.6	49.1	D
KAPO	681	304.9	49.1	C
LG4Q	829	2.9	49.1	C

Comments: CIQ polarity provided by R. DuBerger; MSNY, BGRZ, CHIP, FINE and LOZ polarities supplied by W.-Y. Kim.

Focal Mechanism Solutions

Strike	Dip	Rake
168.70	11.17	63.26
176.98	15.79	71.32
167.18	26.81	67.35
170.87	31.47	70.57
159.73	17.96	55.73
167.17	22.27	62.73
156.11	28.90	57.62
161.00	33.23	61.81
146.28	21.09	44.01
154.87	24.81	51.92
142.07	27.99	43.22
149.04	31.61	49.26
338.24	61.98	67.20
341.24	57.39	66.04
139.04	31.61	36.26

total number solutions: 15
grid search: 5°
misfits: 0
comments:

Preferred solution: -solutions similar so use mean; in calculations, use auxiliary plane for solutions 13 and 14

Plane 1:

Strike: 164°
Dip: 27°
Rake: 66°

Plane 2:

Strike: 15°
Dip: 78°
Rake: 107°

P-axis:

Trend: 93°
Plunge: 22°

T-axis:

Trend: 294°
Plunge: 62°

B-axis:

Trend: 187°
Plunge: 9°

Quality: A

good azimuthal coverage and redundancy

Figure Captions:

Figure 7. Seismograms from which polarity data were read by the authors.

Figure 8. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations.

LA CONCEPTION, QUEBEC: 30 JULY 1998

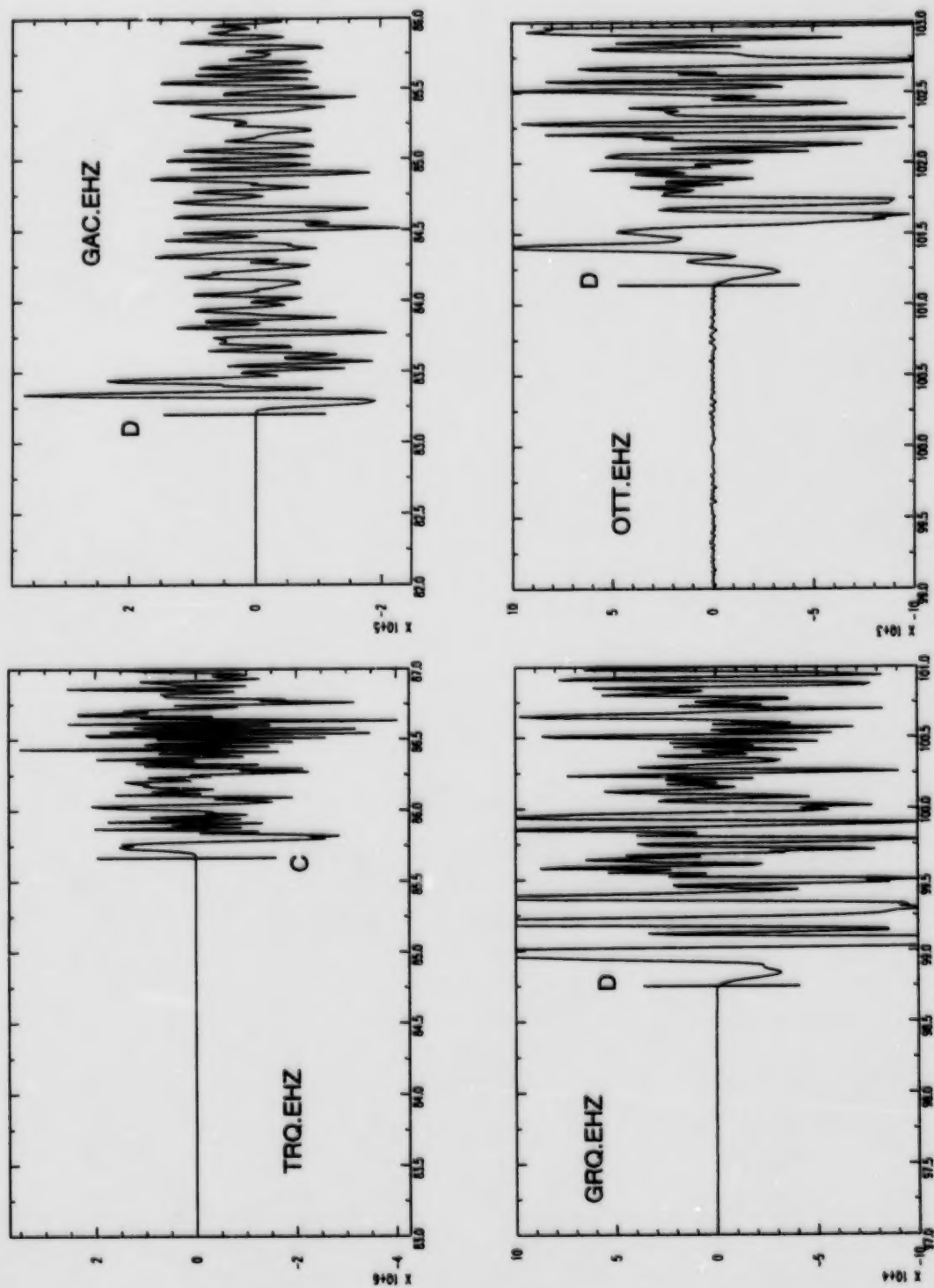


Figure 7a

LA CONCEPTION, QUEBEC: 30 JULY 1998

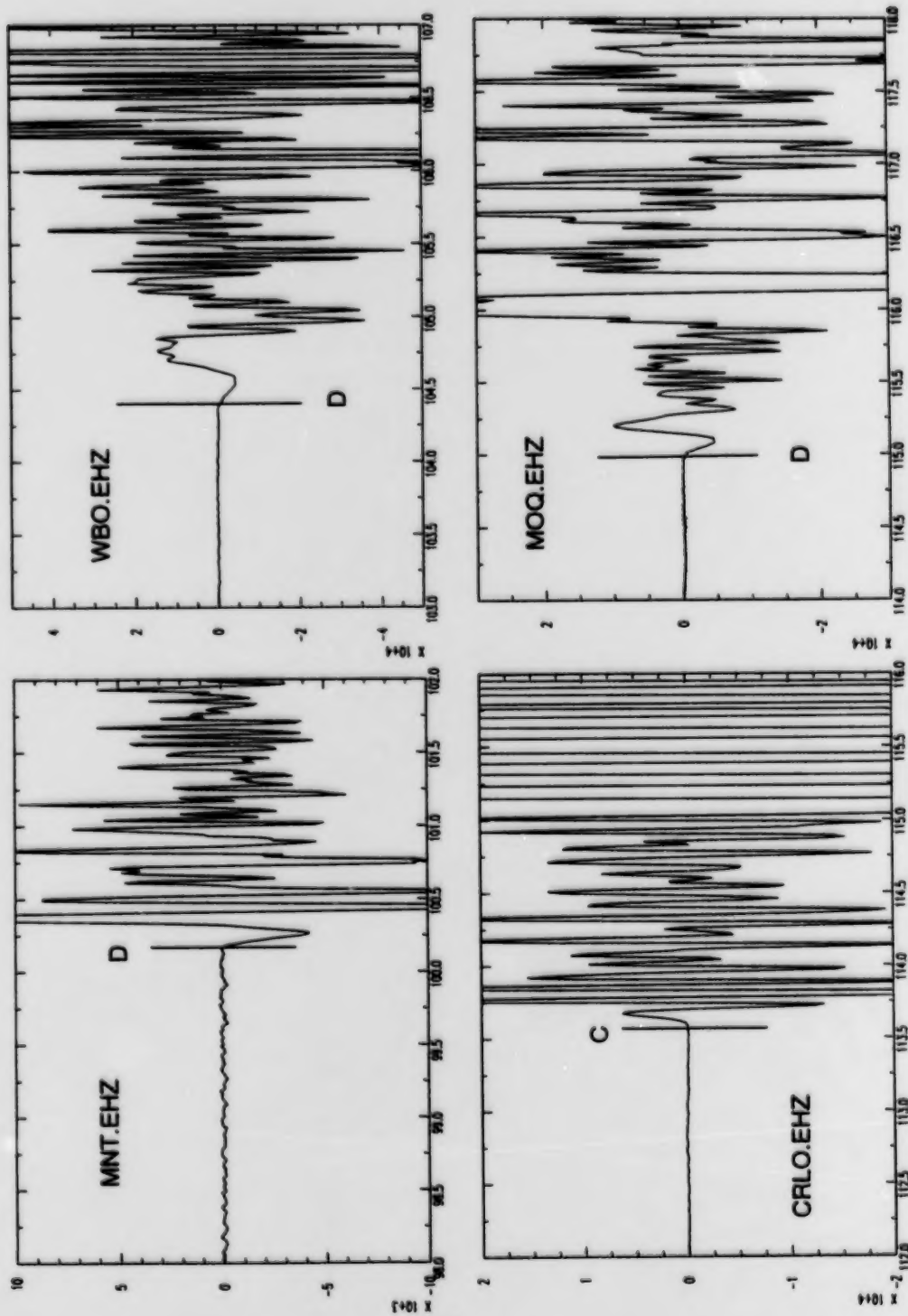


Figure 7b

LA CONCEPTION, QUEBEC: 30 JULY 1998

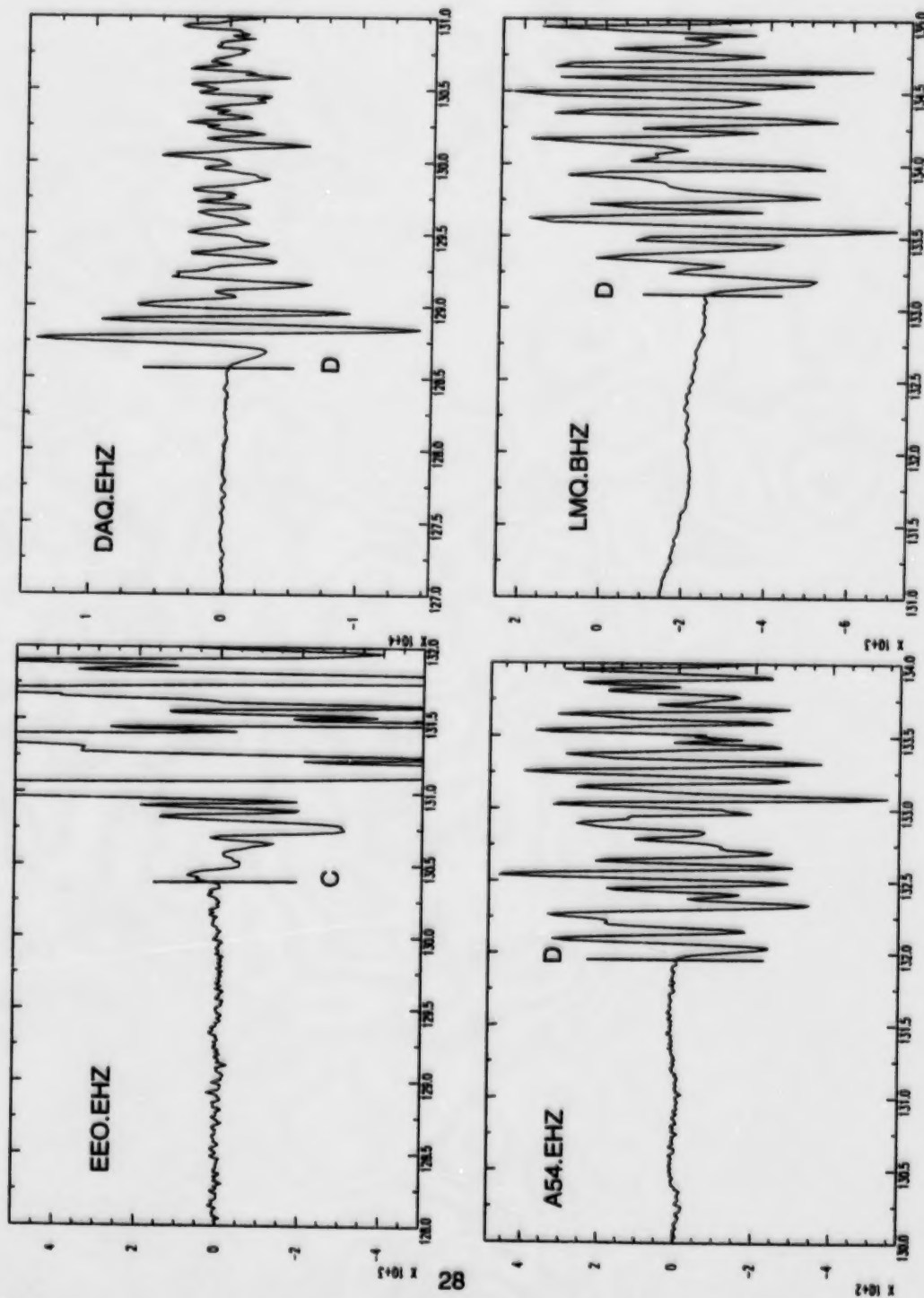


Figure 7c

LA CONCEPTION, QUEBEC: 30 JULY 1998

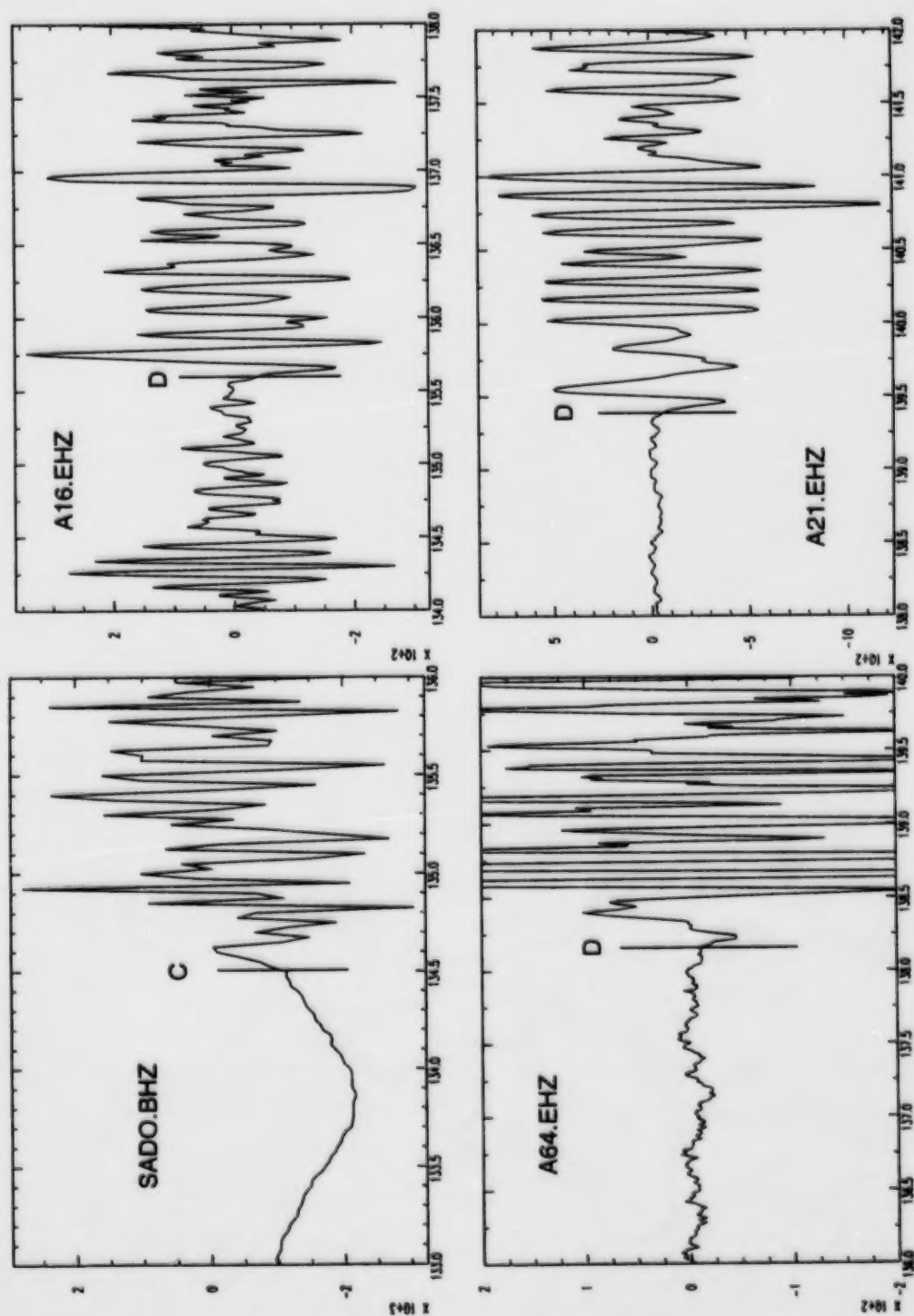


Figure 7d

LA CONCEPTION, QUEBEC: 30 JULY 1998

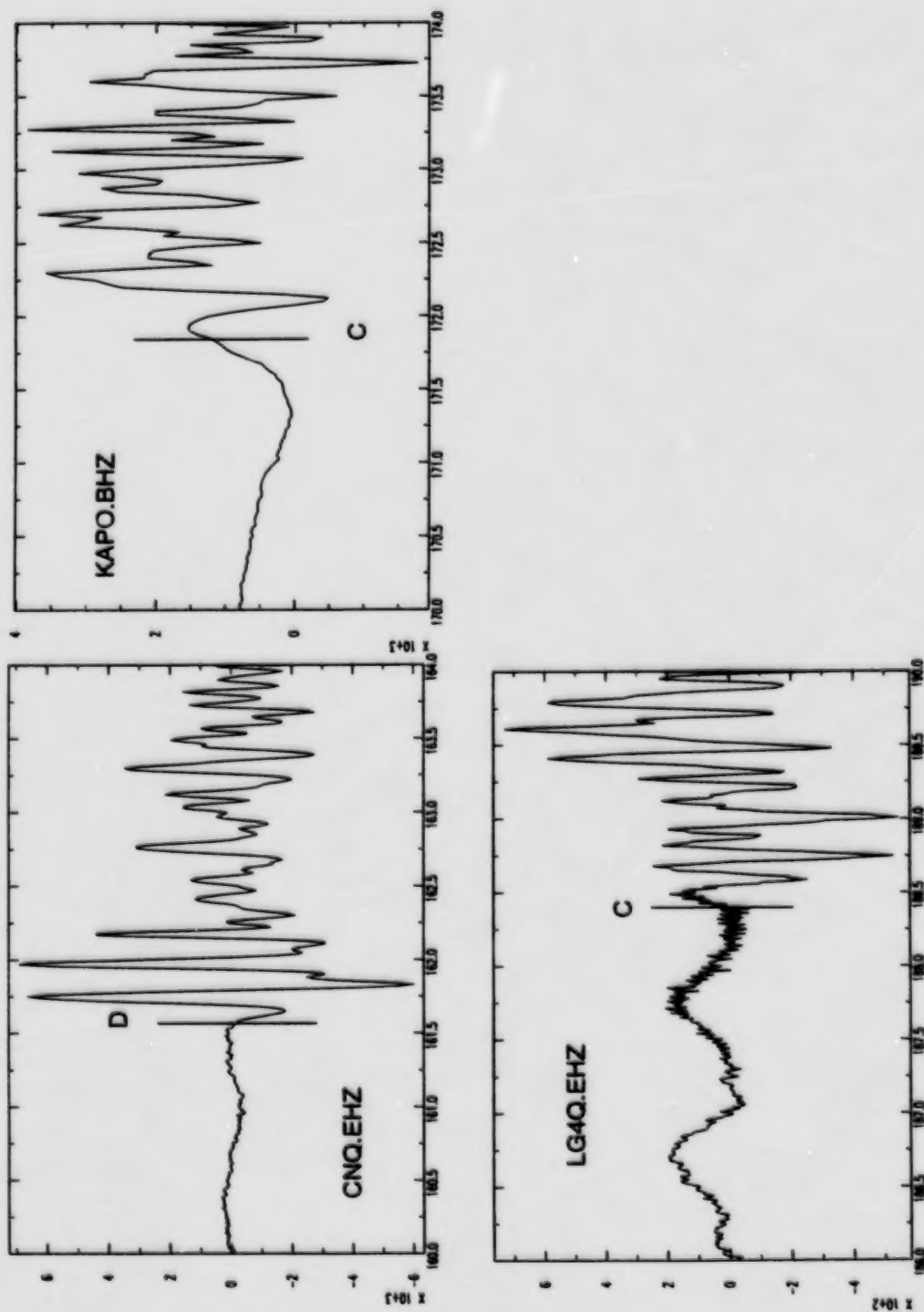


Figure 7e

LA CONCEPTION, QUEBEC: 30 JULY 1998

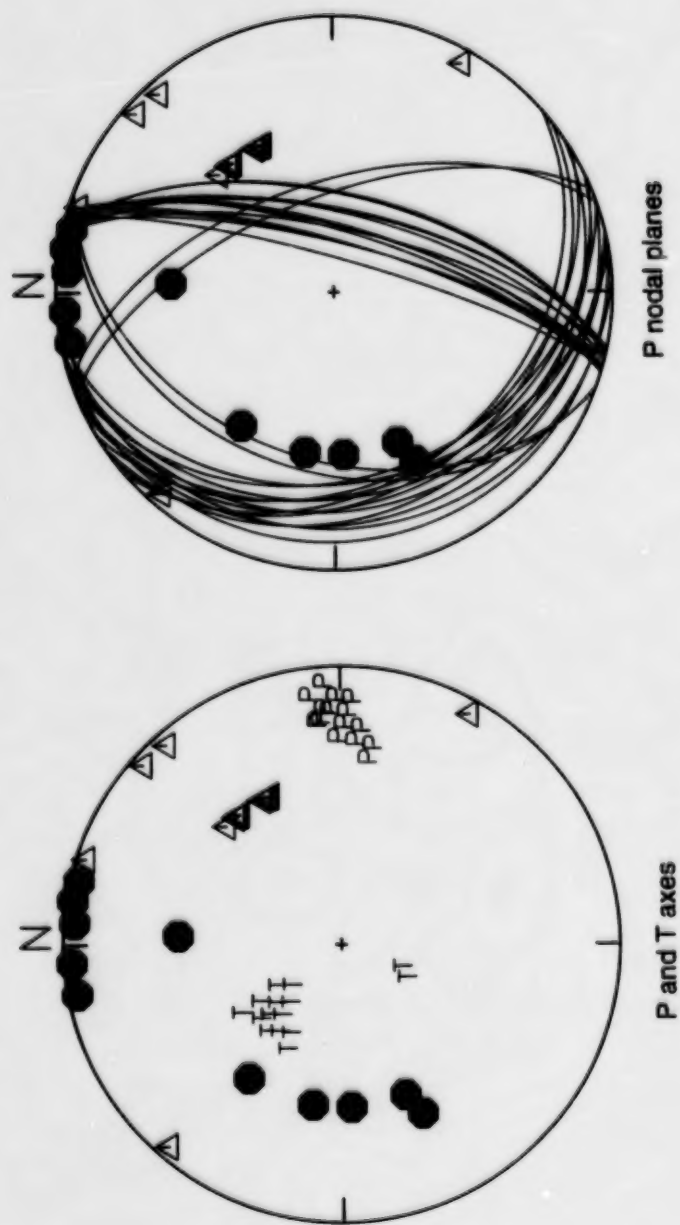


Figure 8

8 SEPTEMBER 1998: LAURENTIAN FAN

Seismic Zone: none
Latitude: 43.78° N
Longitude: 56.40° W
Depth: 18 km (fixed)
Magnitude: 4.3 (M_L)
Origin Time: 06:27:06 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
GBN	444	295.8	49.1	-
DRLN	1094	340.6	49.1	D
LMN	1188	306.7	49.1	-

Focal Mechanism Solutions

total number solutions: 1881 (1238)
grid search: 10°
misfits: 0
comments: may be able to read polarities on some northeastern U. S. stations; not checked; would only marginally improve azimuthal coverage; number of solutions reduced from 1881 to 1238 if DRLN given double weight and others treated as impulsive

Preferred solution: insufficient data to determine
only conclusion is that T axis unlikely to be in NW quadrant (or if it is, plunge must be close to 45°)

Figure Captions:

Figure 9. Digital seismograms from which polarity data were read by the authors.

Figure 10. Focal mechanism solutions. Lower hemisphere projection. Solid symbols indicate compressional first motions and open . Figures show data and stress axes. Nodal planes are not plotted due to the large number of solutions. Solutions shown are based on weighted data.

Laurentian Fan: 8 September 1998

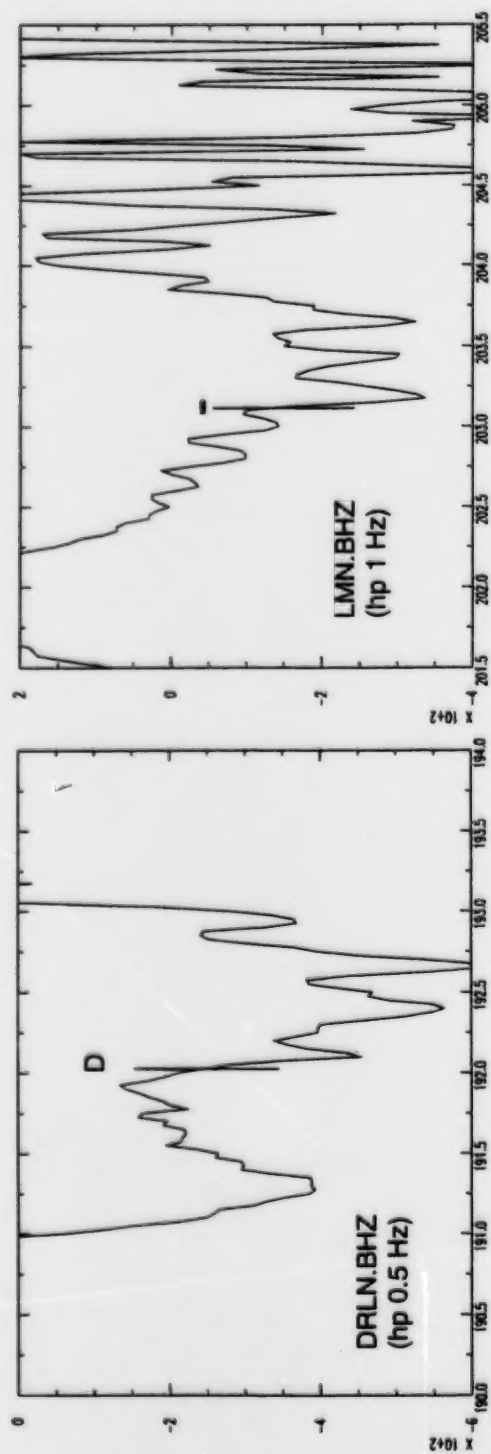


Figure 9

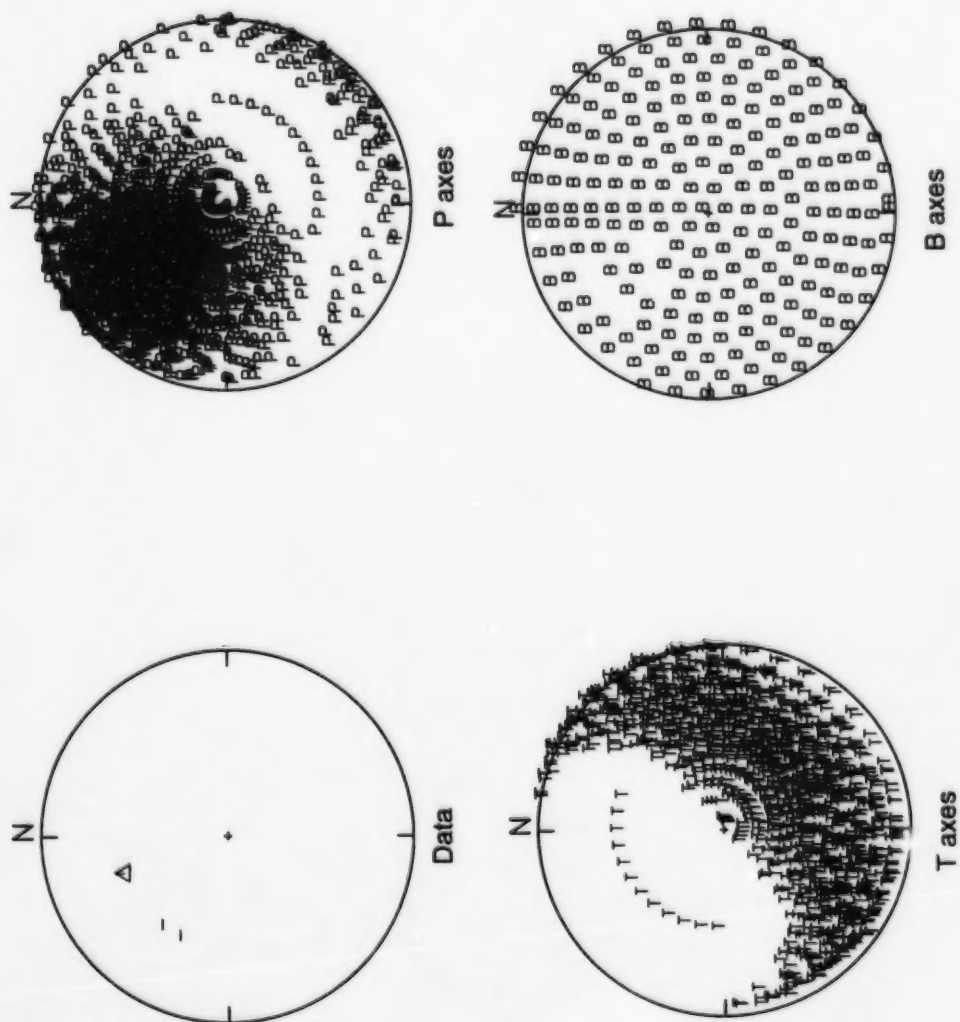


Figure 10

30 SEPTEMBER 1998: DISTRICT OF KEEWATIN, NORTHWEST TERRITORIES

Seismic Zone: Boothia-Ungava
Latitude: 66.82° N
Longitude: 93.22° W
Depth: 18 km (fixed)
Magnitude: 4.4 (m_N)
Origin Time: 16:26:27 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
RES	881	356.8	49.1	C
RES	881	356.8	49.1	>
RES	881	356.8	49.1	F
YKW1	1118	254.5	49.1	C
YKW3	1120	255.0	49.1	C
YKW2	1127	254.4	49.1	C
FRB	1195	95.1	49.1	C
FFC	1431	204.2	49.1	D
KUQ	1589	115.7	49.1	D
INK	1697	294.0	49.1	+
LG4Q	1799	135.5	51.6	+
ULM	1854	185.9	49.6	D
EDM	1870	225.7	49.6	-
SCHQ	1936	120.8	49.6	D
KAPO	2031	157.2	47.4	D
TBO	2038	171.9	47.4	D

Focal Mechanism Solutions

Strike	Dip	Rake
69.05	60.00	90.00
78.92	60.00	90.00
88.78	70.00	90.00
226.59	31.47	70.57
227.97	22.27	62.73
236.73	31.47	70.57
238.11	22.27	62.73
214.00	43.96	60.48
216.27	35.53	53.95
214.43	27.99	43.22
198.64	41.41	40.89
196.99	35.53	30.64
210.04	41.41	40.89
189.33	52.84	16.01
200.92	56.17	22.76
192.75	50.73	8.29
195.65	50.00	0.00
198.56	50.73	-8.29
190.39	56.17	-22.76
201.98	52.84	-16.01
195.65	60.50	-28.34
206.26	56.17	-22.76
187.02	64.34	16.10
185.12	60.50	5.73
196.41	61.98	11.17
193.89	60.00	0.00
191.37	61.98	-11.17

Strike	Dip	Rake
202.66	60.5	-5.73
200.75	64.34	-16.10
194.38	70.32	3.62
192.99	71.25	-7.10

total number solutions: 31 (263)

grid search: 10° (5°)

misfits: 0 (0)

comments: FCC not working; IGL not available
to reduce number of solutions we tried weighting the data by giving a single weight to S waves and emergent P waves and double weight to all impulsive P waves; for a 10° search and 1 misfit (always LG4Q) the number of solutions was reduced to 12 but the range of solutions did not change

Preferred solution: insufficient data to determine

Fault Plane:

Strike: undetermined (most solutions have 1 nodal plane near east-west and another in the southwest quadrant)

Dip: shallow to moderate

Rake: normal or near-normal can be ruled out; range from pure strike-slip to pure thrust possible

P-axis:

Trend: S to SW

Plunge: shallow to moderate

T-axis:

Trend: approx. NE

Plunge: undetermined

B-axis:

Trend: SW-NW quadrant or ENE octant

Plunge: near horizontal if ENE; undetermined otherwise

Figure Captions:

Figure 11. Seismograms from which polarity data were read by the authors.

Figure 12. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are

also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. Stress data based on 5° grid search; nodal planes based on 10° grid search.

DISTRICT OF KEEWATIN, NORTHWEST TERRITORIES: 30 SEPTEMBER 1998

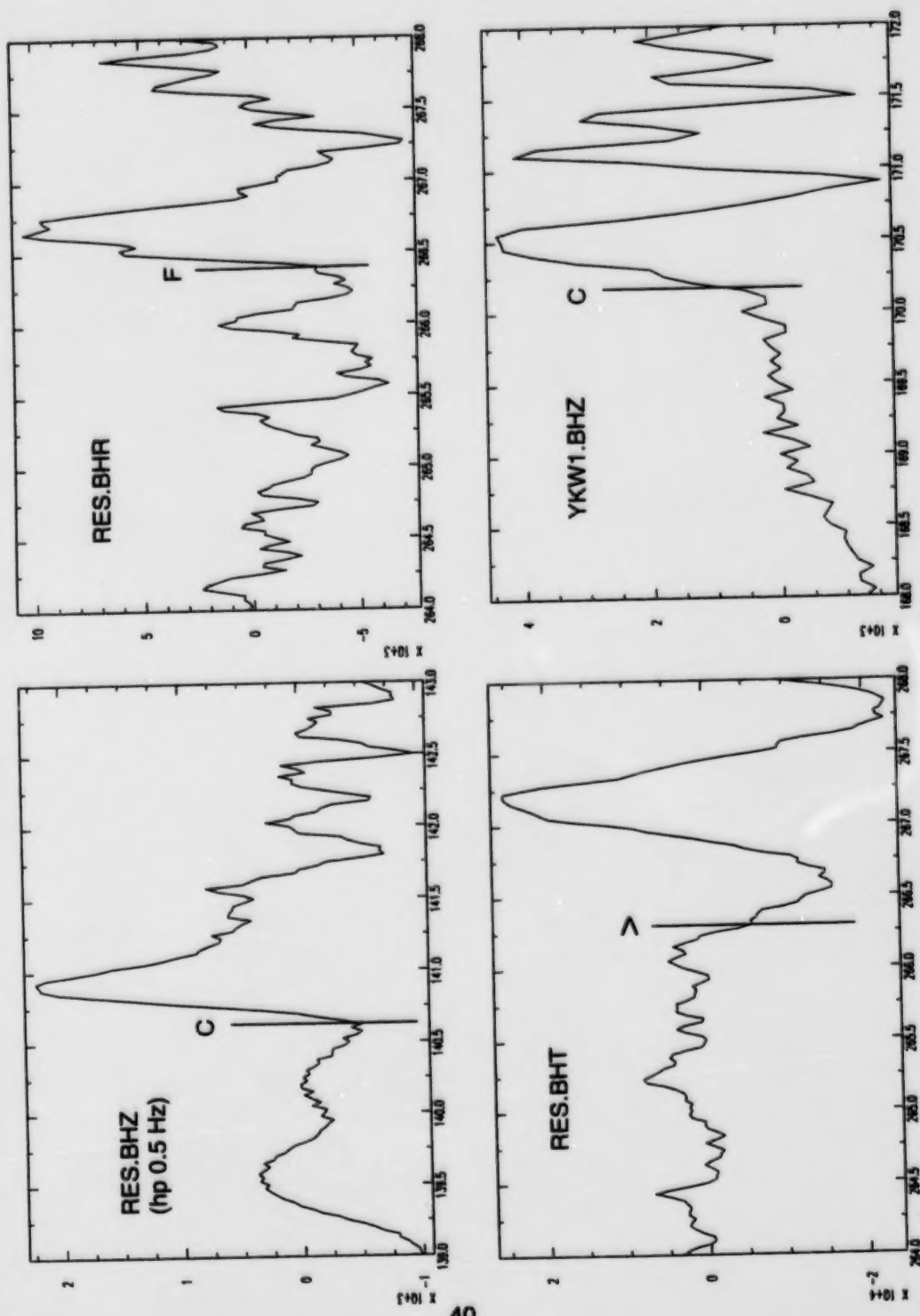


Figure 11a

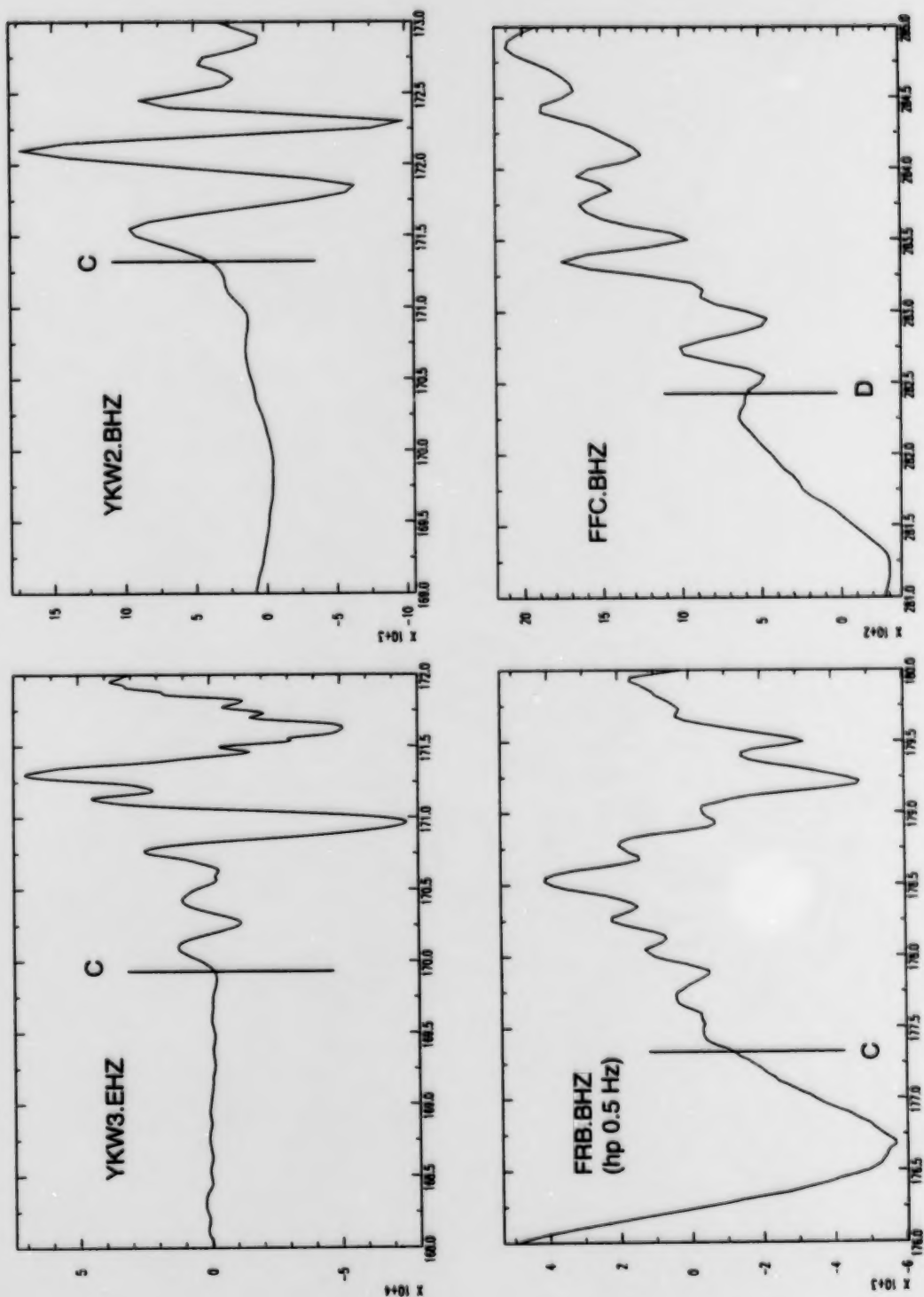


Figure 11b

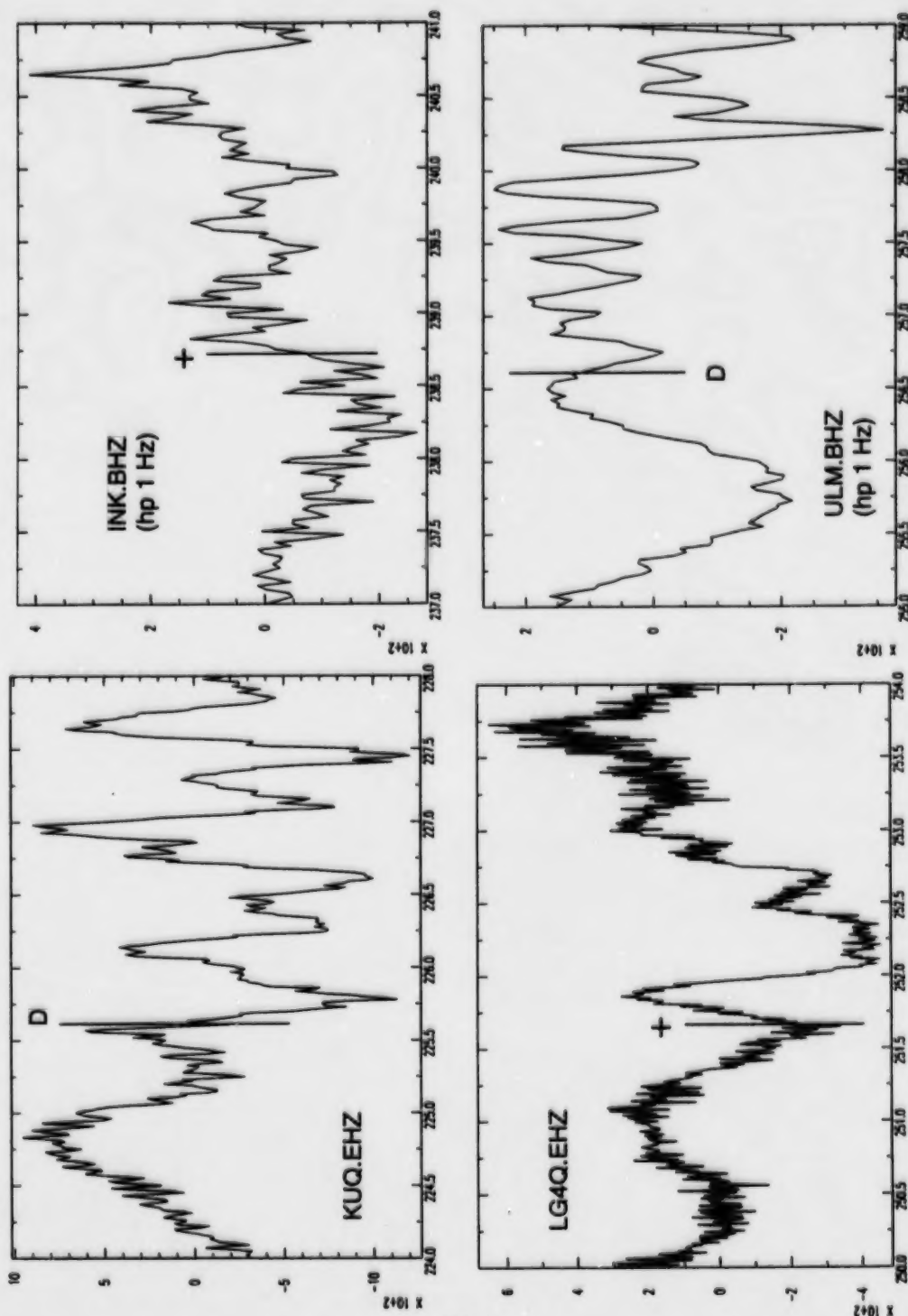


Figure 11c

DISTRICT OF KEEWATIN, NORTHWEST TERRITORIES: 30 SEPTEMBER 1998

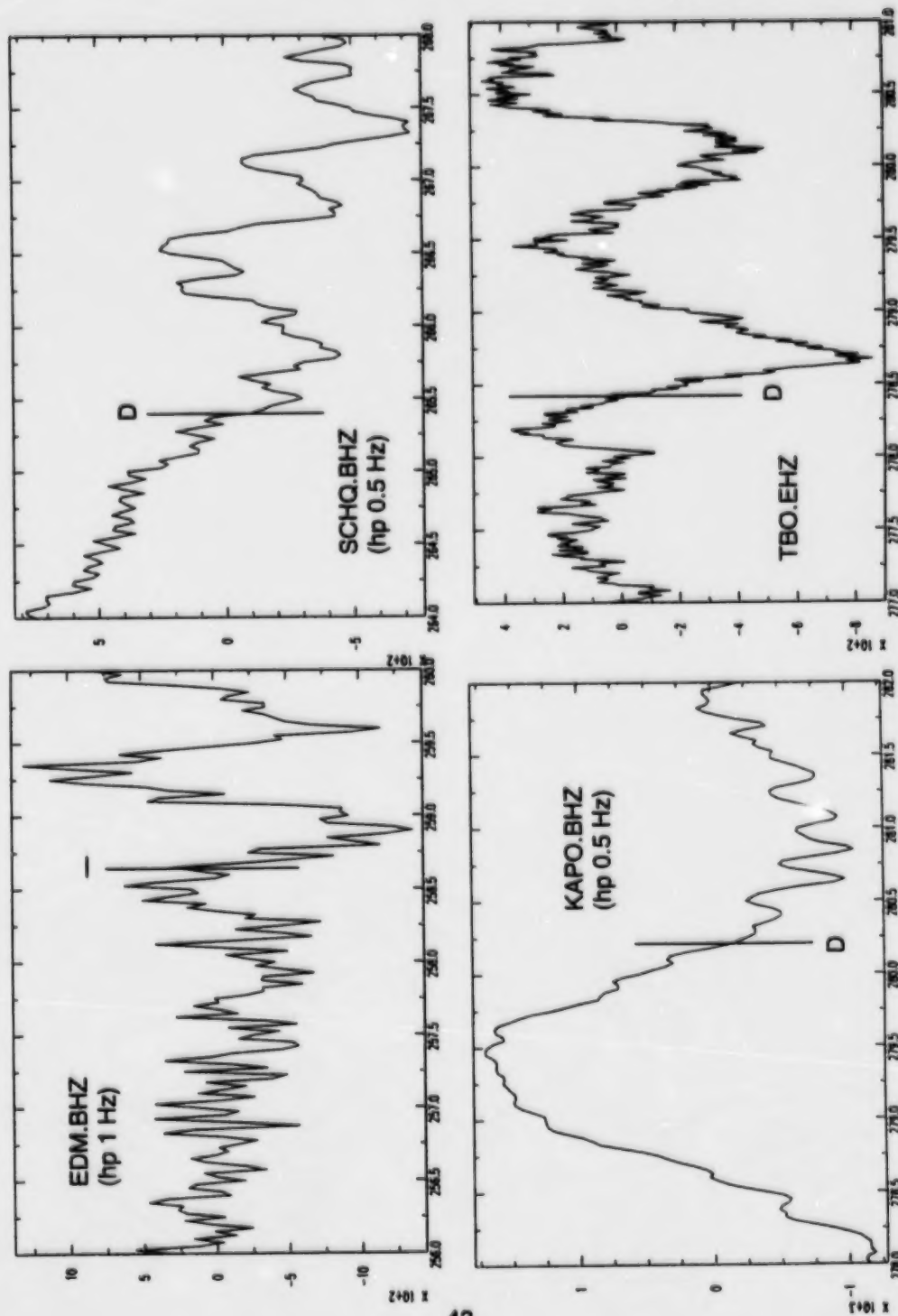


Figure 11d

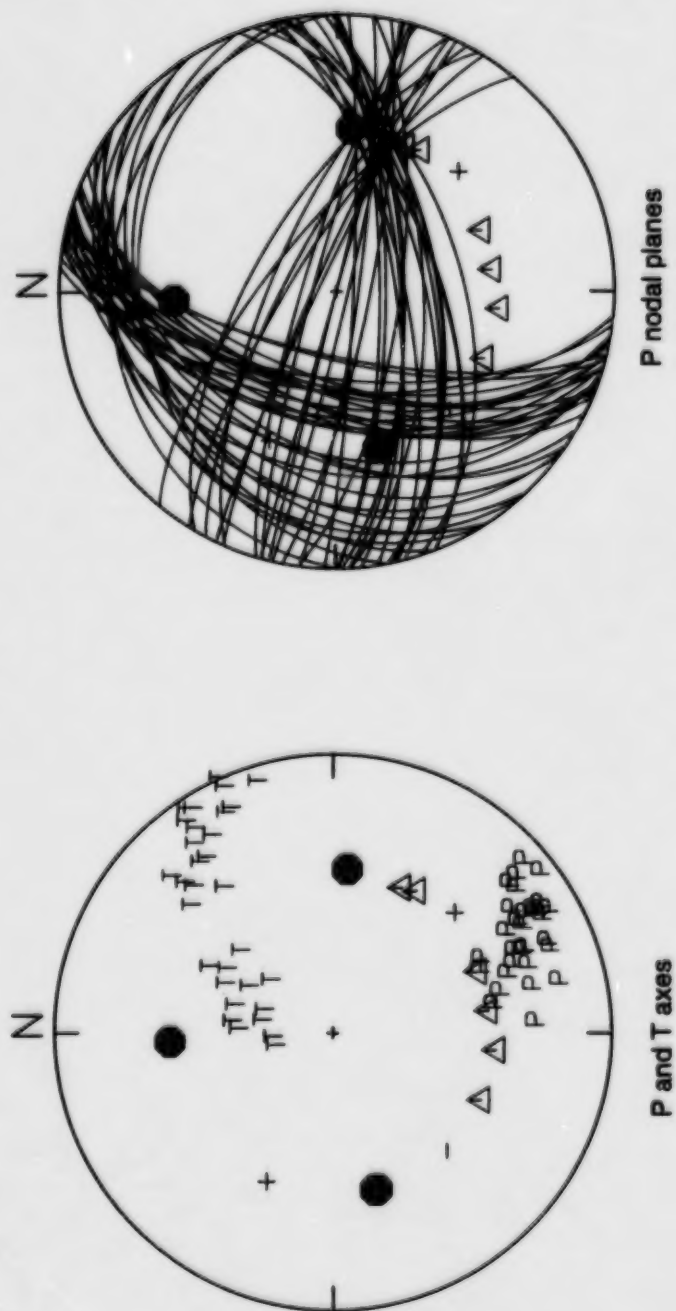


Figure 12

13 OCTOBER 1998: LAURENTIAN SLOPE

Seismic Zone: none
Latitude: 39.47° N
Longitude: 52.84° W
Depth: 18 km (fixed)
Magnitude: 4.1 (M_L)
Origin Time: 07:28:33 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
GBN	971	315.6	49.1	C
DRLN	1149	342.7	49.1	+
LMN	1209	309.8	49.1	C
GSQ	1546	317.4	49.1	-
CNQ	1628	317.1	49.1	-
A21	1635	309.5	49.1	+

Focal Mechanism Solutions

Strike	Dip	Rake
32.27	50.73	77.04
231.69	41.03	74.66
237.82	41.41	40.89
169.09	58.23	-47.57
208.10	42.27	-17.14
200.41	48.36	-18.88
206.89	46.92	-14.51
213.65	45.86	-9.85
166.91	69.30	-40.89

Strike	Dip	Rake
162.49	79.45	-44.01
181.43	65.60	-32.73
176.18	74.24	-37.25

total number solutions: 1799 (12)
grid search: 10° (5°)
misfits: 0
comments: may be able to read polarities on some northeastern U. S. stations; not checked; would only marginally improve azimuthal coverage; number of solutions reduced from 1799 to 12 if LMN and GBN given double weight and all others treated as impulsive

Preferred solution: insufficient data to determine
Fault Plane:
Strike: undetermined
Dip: $\geq 40^\circ$
Rake: not pure normal
P-axis:
Trend: SE quadrant
Plunge: shallow to moderate
T-axis:
Trend: near SW or in ENE octant
Plunge: undetermined
B-axis:
Trend: WSW to NE (most likely near NW)
Plunge: shallow to moderate

Figure Captions:

Figure 13. Seismograms from which polarity data were read by the authors.

Figure 14. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. Solutions shown are based on weighted data.

Laurentian Slope: 13 October 1998

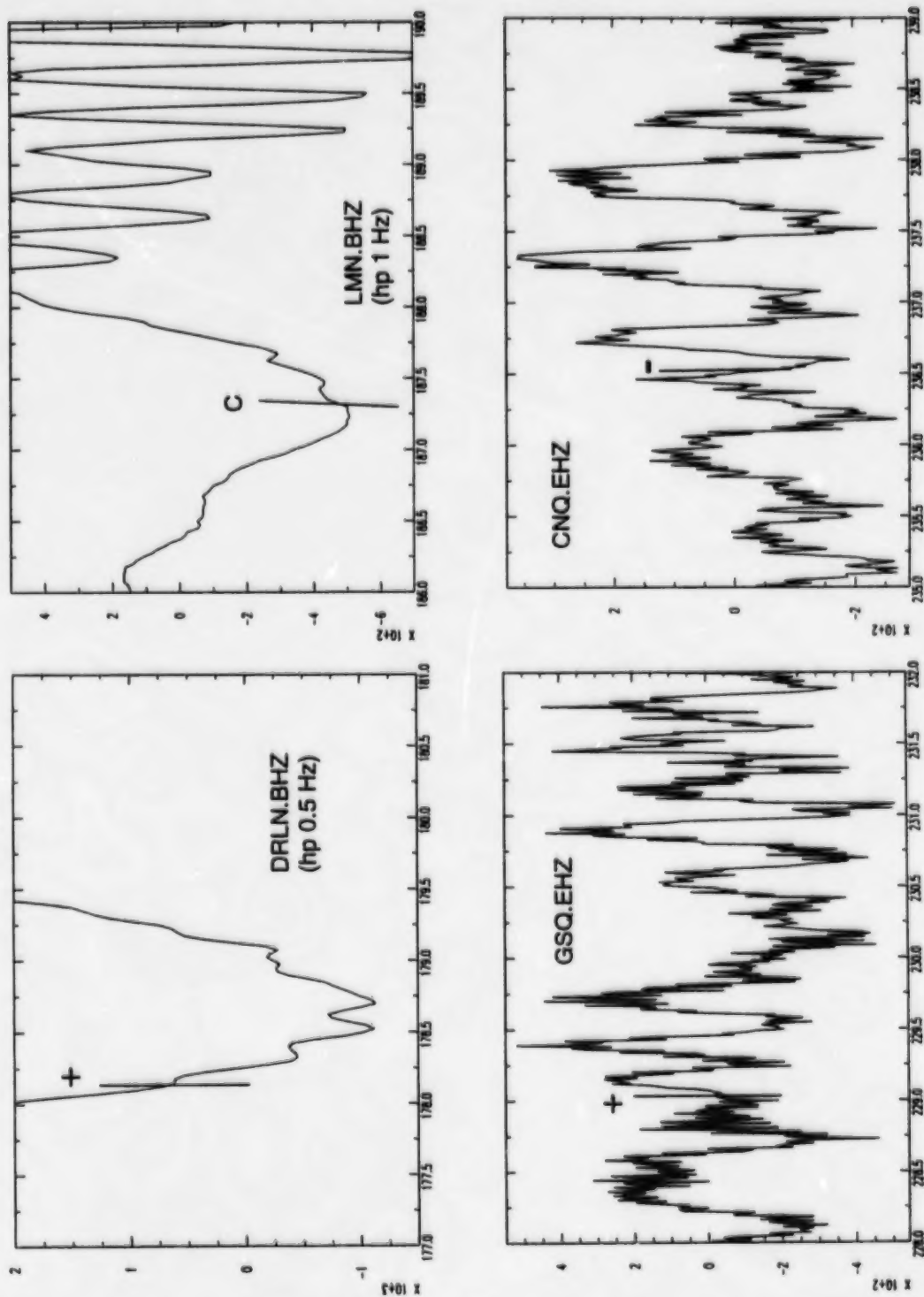


Figure 13a

Laurentian Slope: 13 October 1998

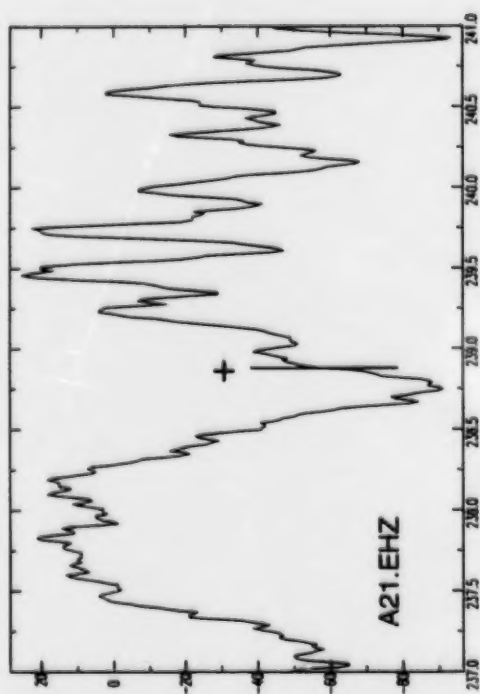


Figure 13b

Laurentian Slope: 13 October 1998

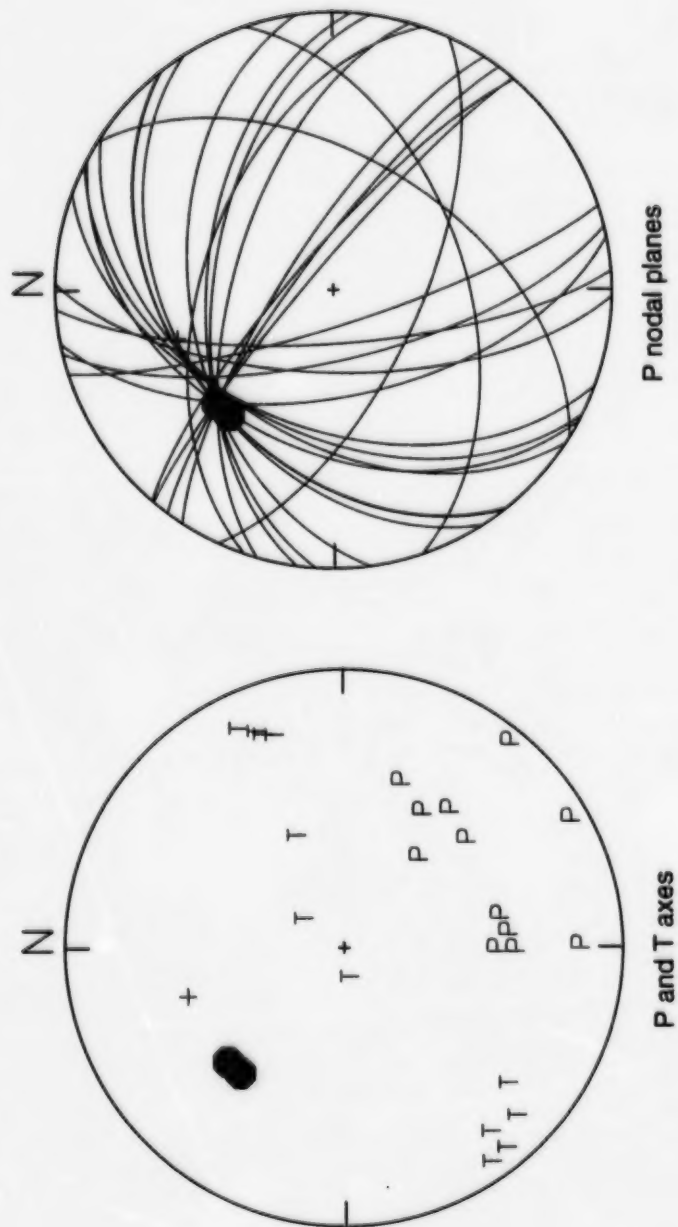


Figure 14

22 OCTOBER 1998: NE of MATANE, QUEBEC

Seismic Zone: lower St. Lawrence
Latitude: 49.34° N
Longitude: 66.82° W
Depth: 18 km (fixed)
Magnitude: 4.1 (m_N)
Origin Time: 09:43:35 (UT)
Comments: felt in lower St. Lawrence region

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
ICQ	34	300.9	-64.3	D
GSQ	51	203.1	-71.1	C
CNQ	87	267.1	-78.8	D
SMQ	98	5.3	-79.7	D
MNQ	189	314.0	49.1	C
A21	276	230.2	49.1	D
A64	279	234.2	49.1	C
A61	300	234.1	49.1	-
A16	312	229.8	49.1	+
LMQ	324	233.8	49.1	+
LMN	419	157.9	49.1	D
DPQ	530	238.5	49.1	C
SCHQ	611	359.9	49.1	C
TRQ	672	241.9	49.1	C
DRLN	682	87.3	49.1	C
LG4Q	691	316.1	49.1	+
GAC	767	241.5	49.1	C
EEO	958	256.5	49.1	C
KAPO	1133	276.6	49.1	-

Focal Mechanism Solutions

Strike	Dip	Rake
250.00	20.00	90.00
236.53	20.59	75.65
244.41	25.46	78.30
222.95	22.27	62.73
217.83	28.90	57.62
227.85	33.23	61.81
200.31	27.99	43.22
207.27	31.61	49.26
218.18	35.53	53.95
201.51	34.78	42.19
207.49	38.29	47.00
191.07	38.29	36.20

total number solutions: 12
 grid search: 5°
 # misfits: 0
 comments:

Preferred solution: fault plane orientations similar, although there is some variation in rake; use mean

Plane 1:

Strike: 219°
 Dip: 30°
 Rake: 58°

Plane 2:

Strike: 74°
 Dip: 67°
 Rake: 107°

P-axis:

Trend: 152°
 Plunge: 20°

T-axis:
Trend: 12°
Plunge: 63°
B-axis:
Trend: 247°
Plunge: 16°
Quality: A
good azimuthal coverage and redundancy

Figure Captions:

Figure 15. Seismograms from which polarity data were read by the authors.

Figure 16. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations.

NE of Matane, Quebec: 22 October 1998

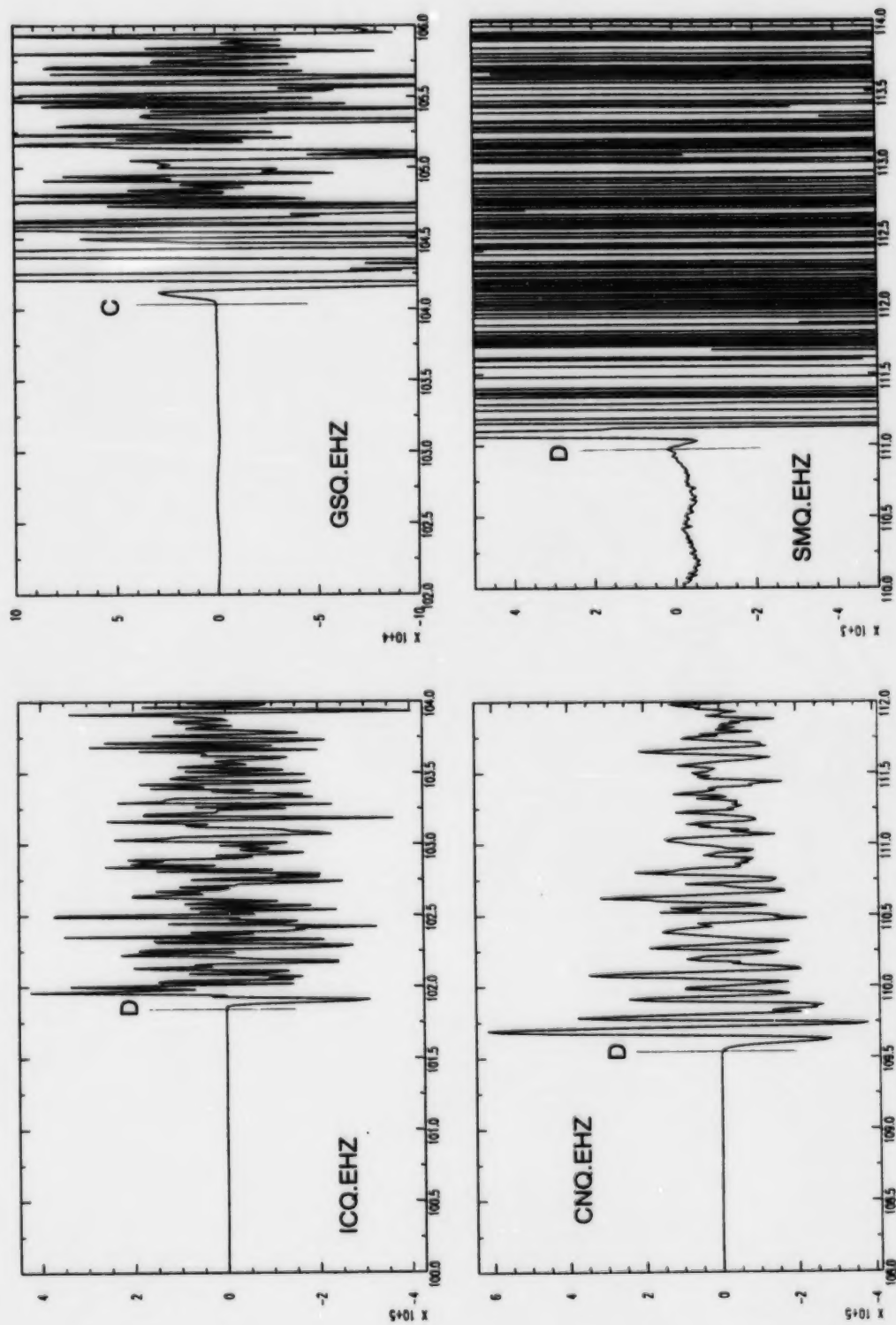


Figure 15a

NE of Matane, Quebec: 22 October 1998

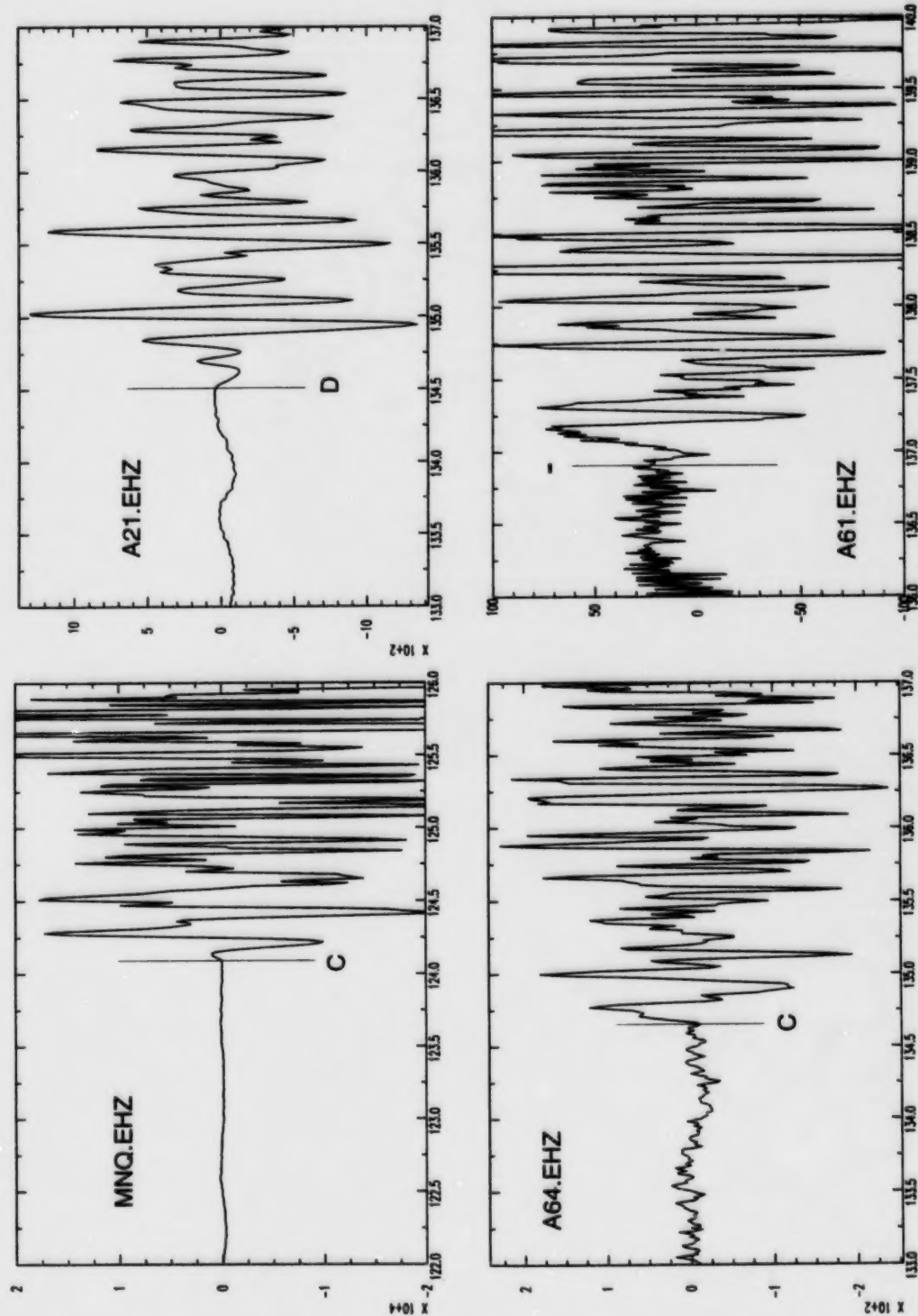


Figure 15b

NE of Matane, Quebec: 22 October 1998

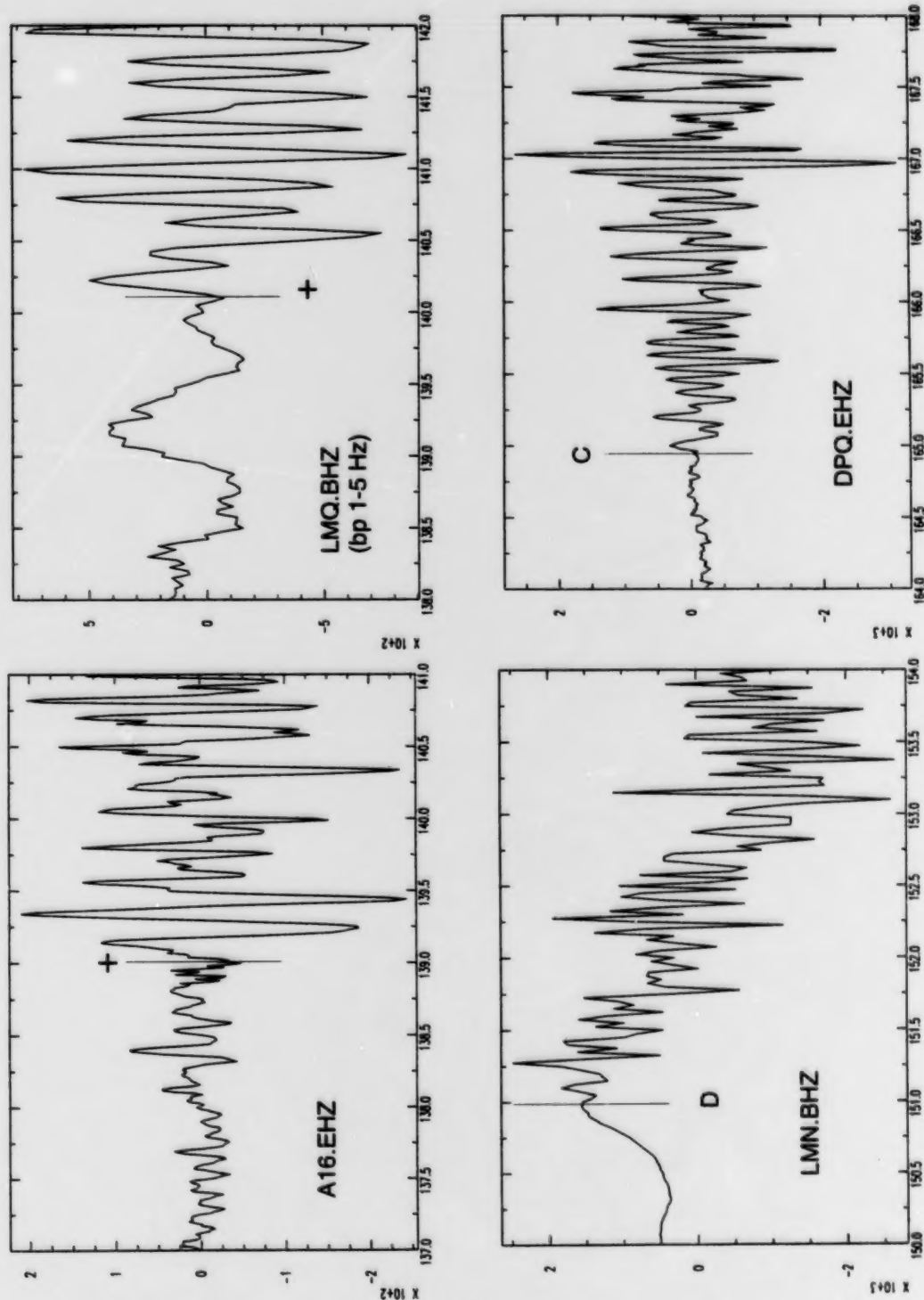


Figure 15c

NE of Matane, Quebec: 22 October 1998

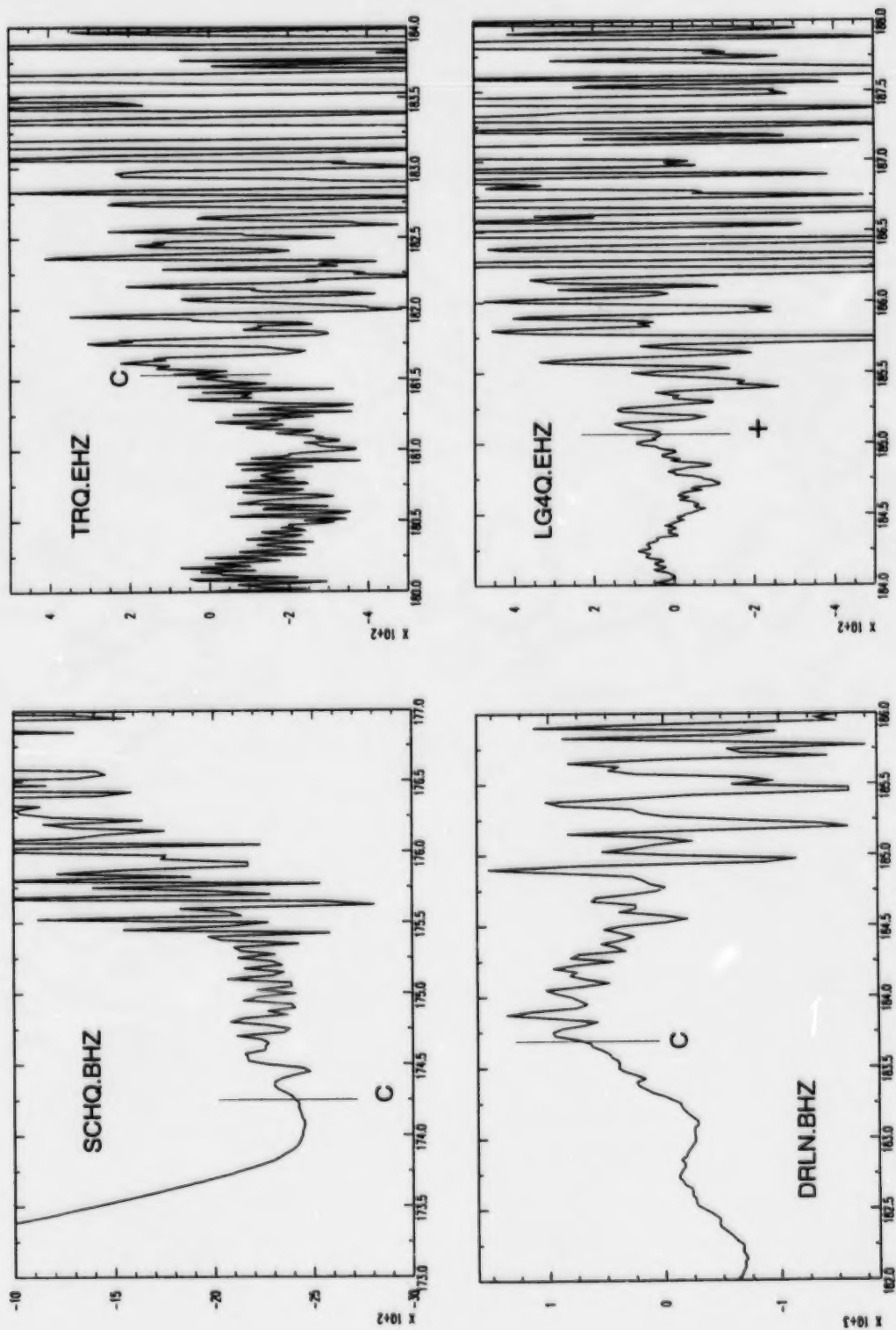


Figure 15d

NE of Matane, Quebec: 22 October 1998

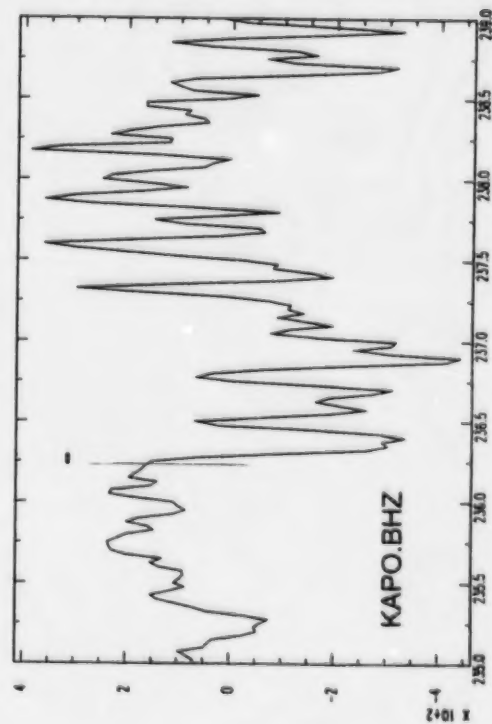
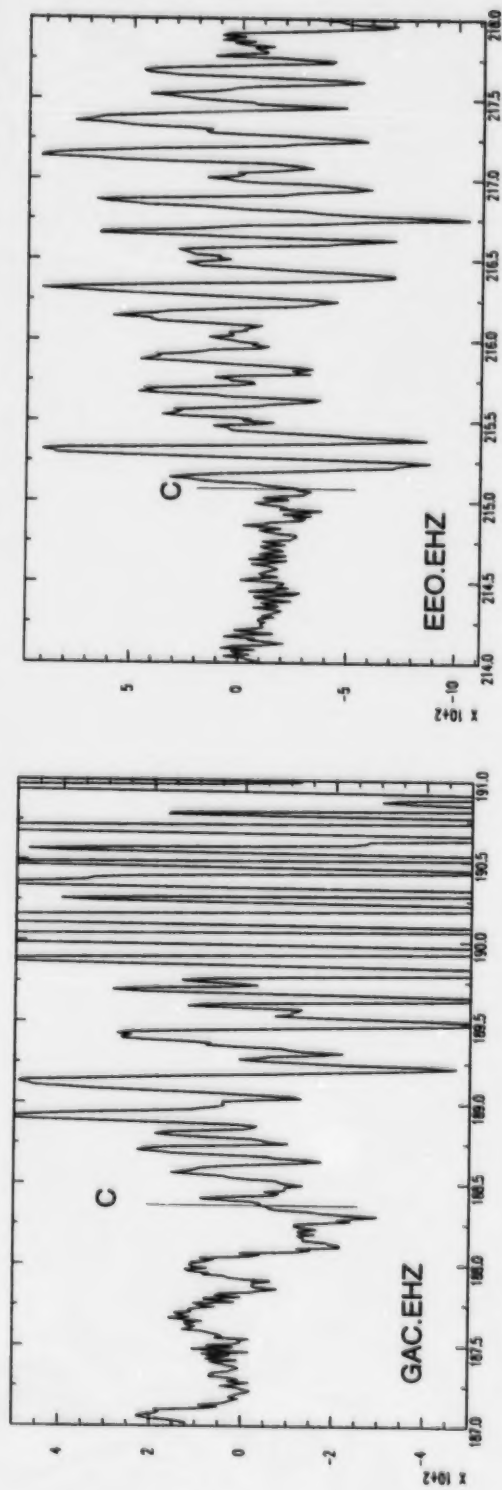


Figure 15e

NE OF MATANE, QUEBEC: 22 OCTOBER 1998

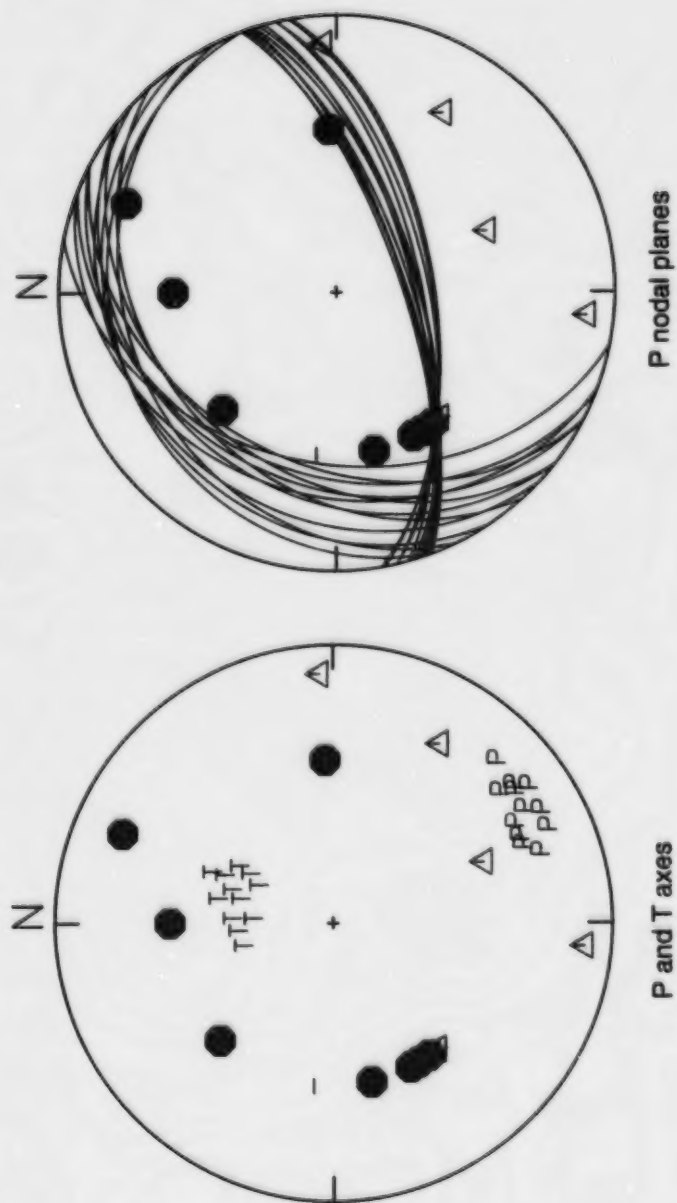


Figure 16

23 NOVEMBER 1998: AXEL HEIBERG ISLAND, NORTHWEST TERRITORIES

Seismic Zone: Sverdrup
Latitude: 80.15° N
Longitude: 90.04° W
Depth: 18 km (fixed)
Magnitude: 4.2 (M_L)
Origin Time: 07:09:13 (UT)
Comments: -recalculation of magnitude using data from ALE suggests magnitude is less than 4 (m_N 3.6)

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
ALE	528	47.4	49.1	D
RES	622	193.4	49.1	+
IGL	1225	164.6	49.1	D
INK	1787	247.5	51.6	-
YKW3	2112	216.3	45.1	+

Focal Mechanism Solutions

Strike	Dip	Rake
113.79	45.86	-76.00
112.23	46.92	-69.25
112.58	46.03	-54.04
113.30	41.41	40.89
139.11	41.41	40.89
144.91	41.41	40.89
132.16	42.06	31.11
138.24	44.81	35.53
138.26	42.06	31.11

Strike	Dip	Rake
128.82	45.00	0.00
121.77	45.22	-4.98
121.88	45.86	-9.85
128.83	45.22	-4.98
115.70	48.36	-18.88
122.19	46.92	-14.51
128.94	45.86	-9.85
122.76	48.36	-18.88
129.25	46.92	-14.51
136.00	45.86	-9.85
123.66	50.14	-22.91
129.82	48.36	-18.88
136.31	46.92	-14.51
129.13	50.00	0.00
135.65	50.18	4.18
122.62	50.18	-4.18
136.96	50.00	0.00
123.99	50.73	-8.29
130.44	50.18	-4.18
125.50	51.62	-12.25
131.82	50.73	-8.29
127.19	52.84	-16.01
133.33	51.62	-12.25
129.11	54.37	-19.53
135.02	52.84	-16.01
129.51	55.00	0.00
135.61	55.15	3.49
132.60	55.15	-3.49

Strike	Dip	Rake
134.93	55.61	-6.93
131.90	57.39	-13.47
137.74	56.36	-10.27
134.98	58.68	-16.48
135.77	60.13	2.88
138.49	60.50	-5.73
137.20	61.98	-11.17

total number solutions: 671 (44)

grid search: 10° (5°)

misfits: 0

comments: 671 solutions if polarities assumed as in table; 44 if ALE and IGL given double weight and all others treated as impulsive

Preferred solution: insufficient data to determine

Fault Plane:

Strike: undetermined

Dip: 40°-60°

Rake: undetermined

P-axis:

Trend: near east-west

Plunge: undetermined

T-axis:

Trend: near north-south

Plunge: < 60°

B-axis:

Trend: southwest quadrant

Plunge: ≤ 60°

Figure Captions:

Figure 17. Seismograms from which polarity data were read by the authors.

Figure 18. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. Note that solutions shown were obtained by including emergent first motions and giving higher weight to impulsive first motions.

Axel Heiberg Island, Northwest Territories: 23 November 1998

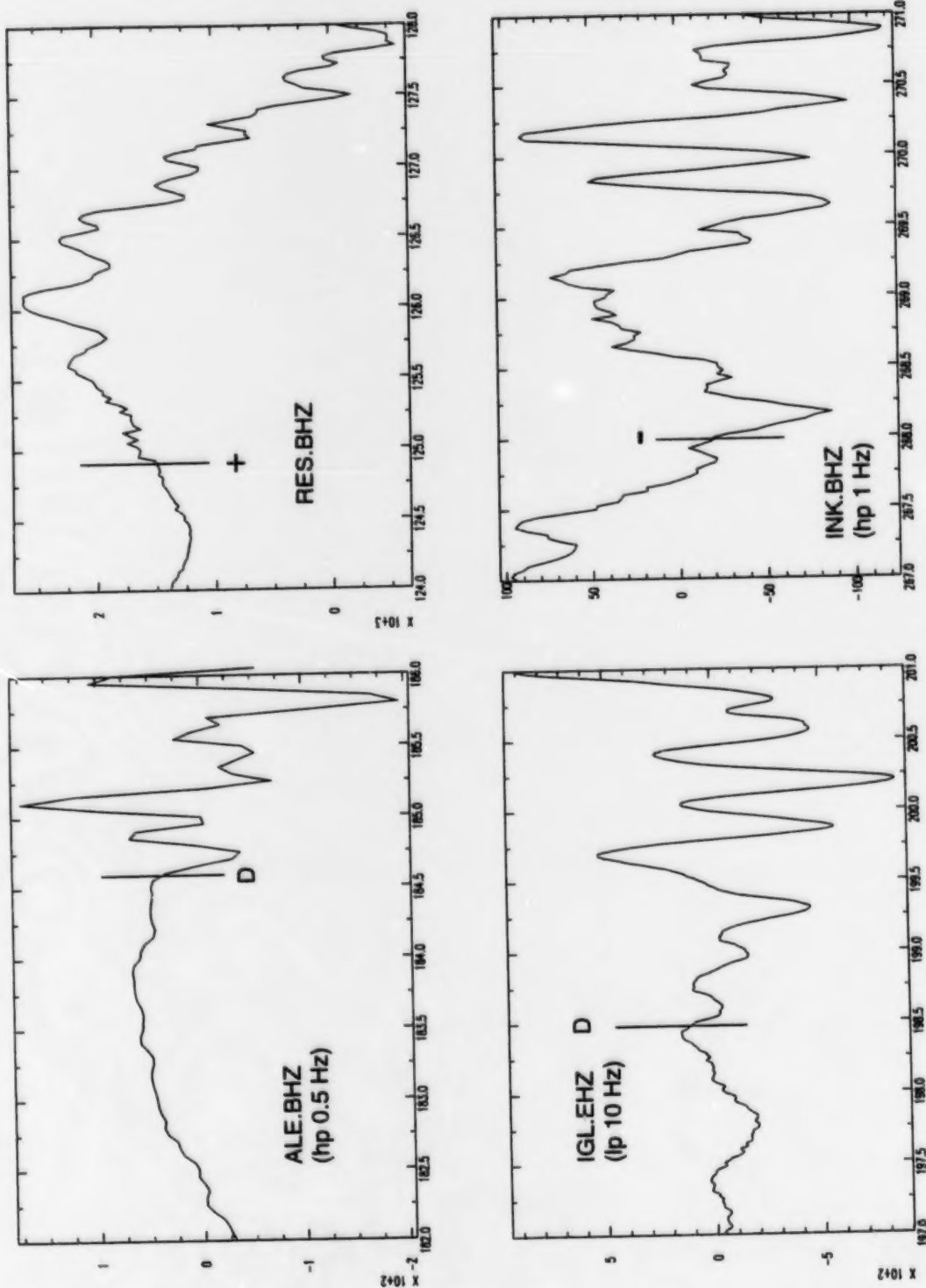


Figure 17a

Axel Heiberg Island, Northwest Territories: 23 November 1998

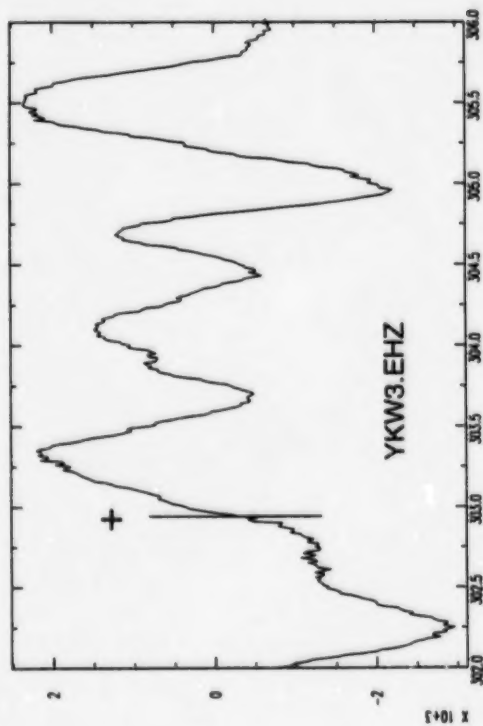


Figure 17b

Axel Heiberg Island, Northwest Territories: 23 November 1998

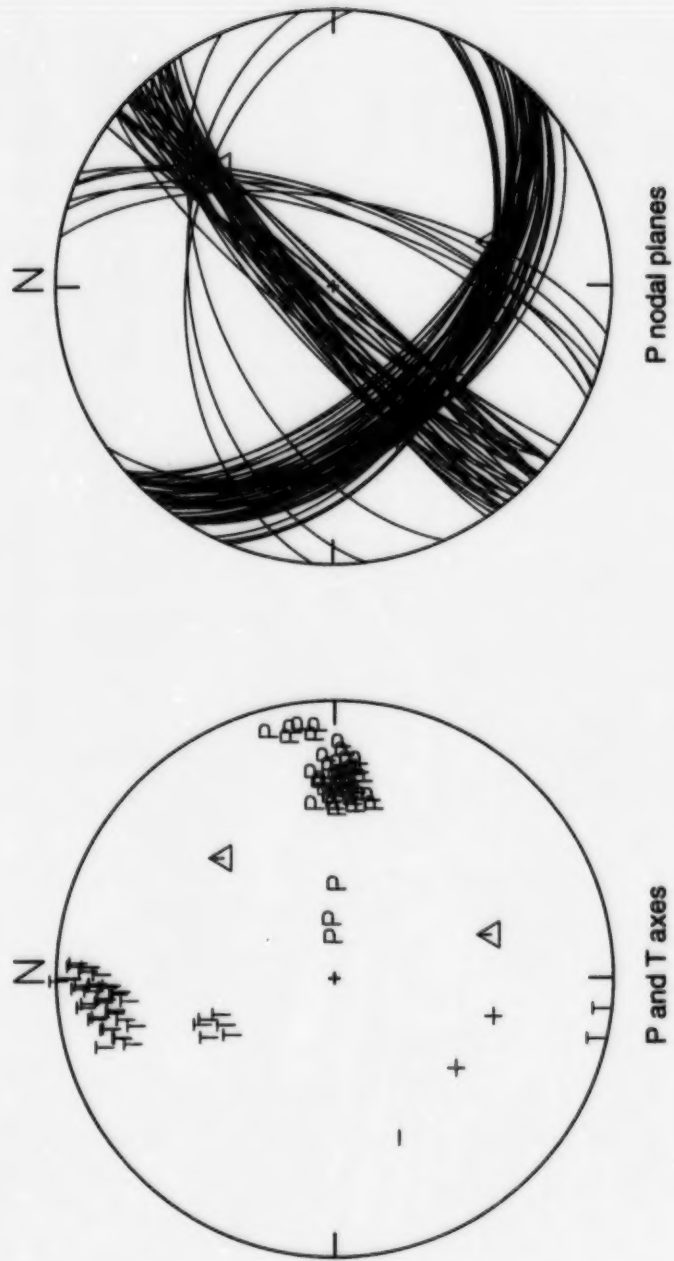


Figure 18

28 NOVEMBER 1998: LABRADOR SEA

Seismic Zone: Labrador Sea
Latitude: 61.03° N
Longitude: 59.03° W
Depth: 18 km (fixed)
Magnitude: 4.1 (M_L)
Origin Time: 22:11:25 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
FRB	578	305.7	49.1	-
KUQ	622	242.6	49.1	C
SCHQ	831	217.2	49.1	-
LG4Q	1223	234.5	49.1	+
SMQ	1296	205.1	49.1	-
MNQ	1318	211.8	49.1	-

Focal Mechanism Solutions

total number solutions: 1881 (415)
grid search: 10° (5°)
misfits: 0
comments: 1881 solutions if data used as in table; 415 if KUQ given double weight and all others treated as impulsive

Preferred solution: insufficient data to determine

Fault Plane:

Strike: undetermined

Dip: $\geq 40^\circ$

Rake: $-60^\circ - +60^\circ$

P-axis:		
	Trend:	SSE or NNW octant
	Plunge:	undetermined
T-axis:		
	Trend:	NE quadrant or WSW octant
	Plunge:	undetermined
B-axis:		
	Trend:	W hemisphere
	Plunge:	undetermined

Figure Captions:

Figure 19. Seismograms from which polarity data were read by the authors.

Figure 20. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. Solutions shown were determined by treating all stations as impulsive and giving double weight to KUQ.

Labrador Sea: 28 November 1998

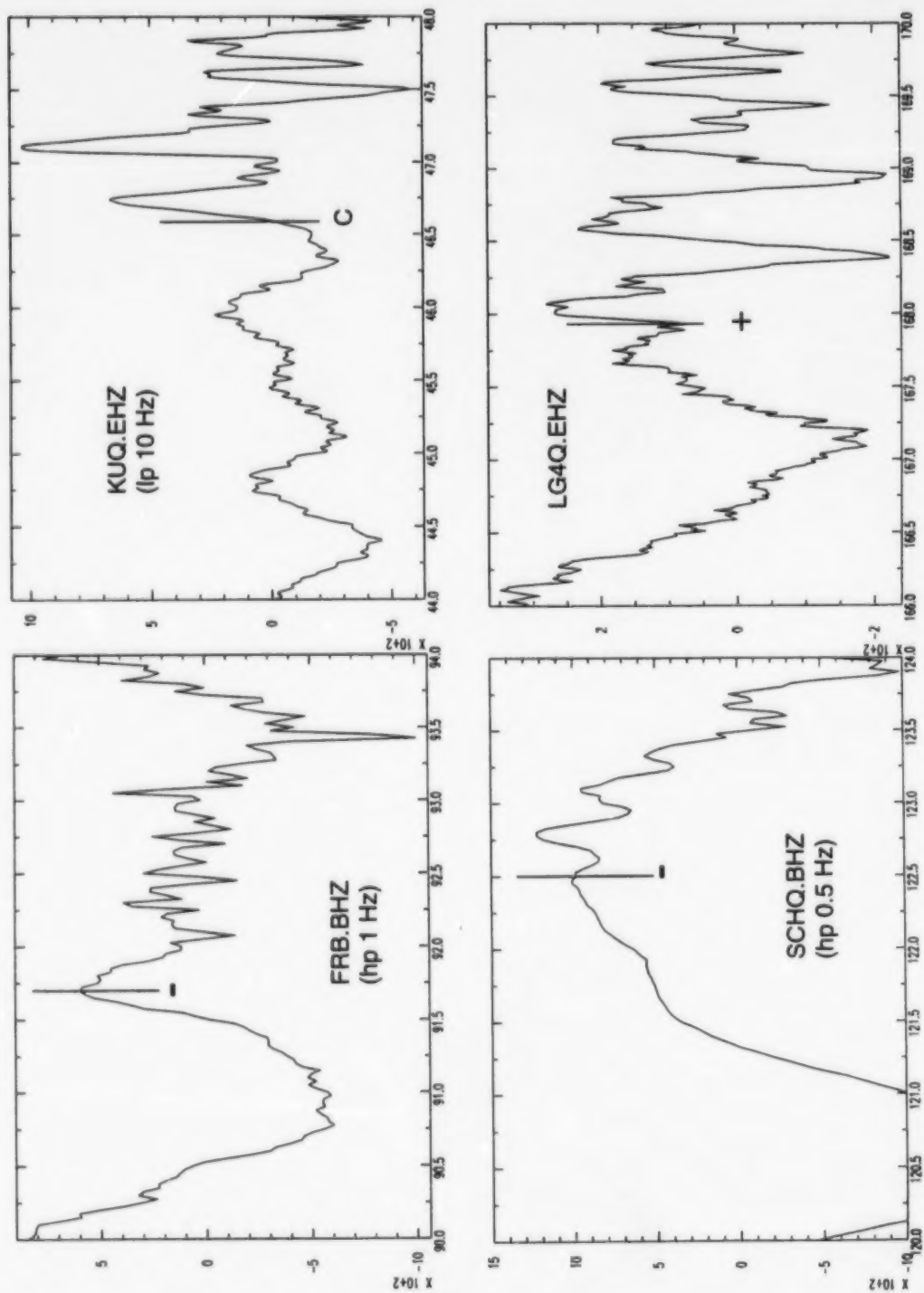


Figure 19a

Labrador Sea: 28 November 1998

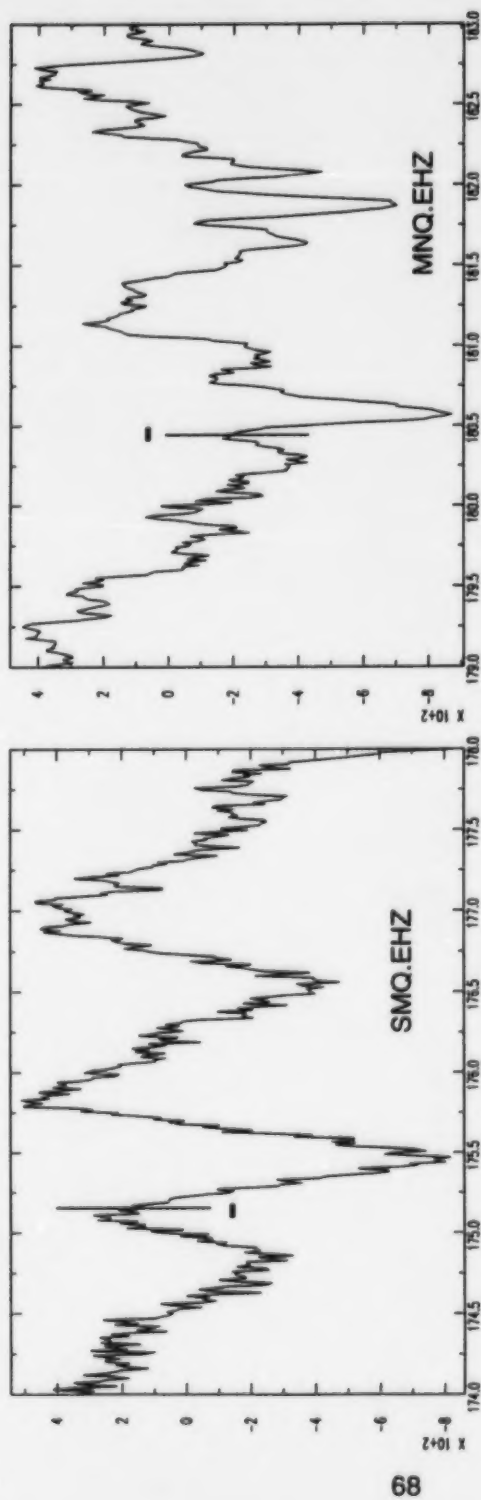


Figure 19b

Labrador Sea: 28 November 1998



Figure 20

22 DECEMBER 1998: AXEL HEIBERG ISLAND, NORTHWEST TERRITORIES

Seismic Zone: Sverdrup
Latitude: 79.91° N
Longitude: 91.04° W
Depth: 18 km (fixed)
Magnitude: 4.4 (m_b)
Origin Time: 17:04:35 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
RES	592	191.1	49.1	D
IGL	1206	162.4	49.1	D
INK	1759	247.1	49.1	C
FRB	1939	145.3	49.6	C
YKW3	2080	215.3	45.1	+
DAWY	2299	248.5	40.5	+
FCC	2366	184.4	40.5	+
WHY	2577	240.1	33.8	+

Focal Mechanism Solutions

total number solutions: 453 (71)
grid search: 5°
misfits: 0

comments: ALE not available; 71 solutions obtained by giving double weight to impulsive first motions and treating others as impulsive (single weight); distribution of stress axes and nodal planes similar to that of 453 solutions obtained by using data as listed in table

Preferred solution: insufficient data to determine

Fault Plane:

Strike: undetermined

Dip: $\geq 40^\circ$

Rake: undetermined

P-axis:

Trend: NW-NE or near S

Plunge: shallow to moderate

T-axis:

Trend: near E-W

Plunge: undetermined

B-axis:

Trend: S hemisphere

Plunge: undetermined

Figure Captions:

Figure 21. Seismograms from which polarity data were read by the authors.

Figure 22. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. Solutions shown obtained by including emergent stations and giving double weight to impulsive first motions.

Axel Heiberg Island, Northwest Territories: 22 December 1998

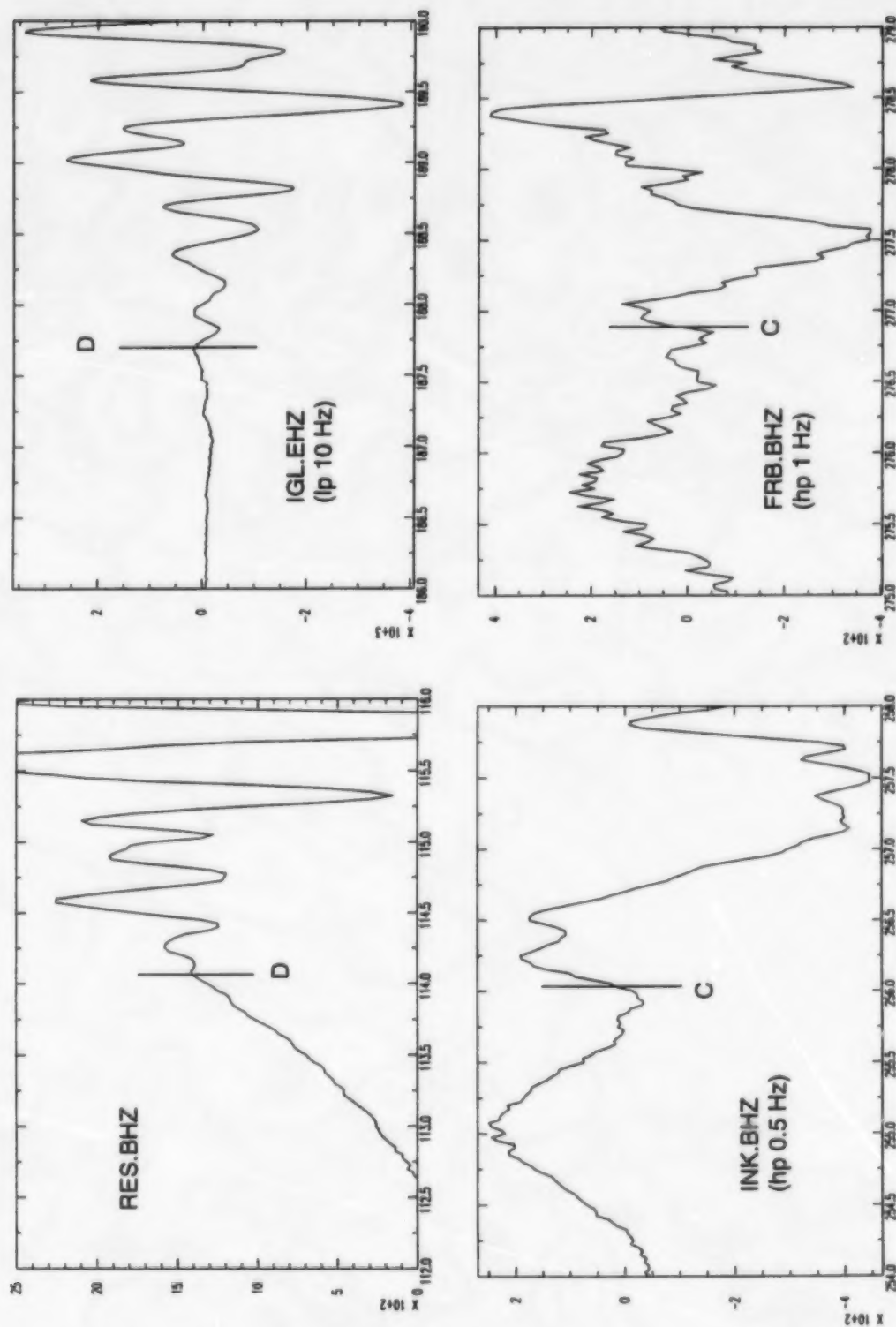


Figure 21a

Axel Heiberg Island, Northwest Territories: 22 December 1998

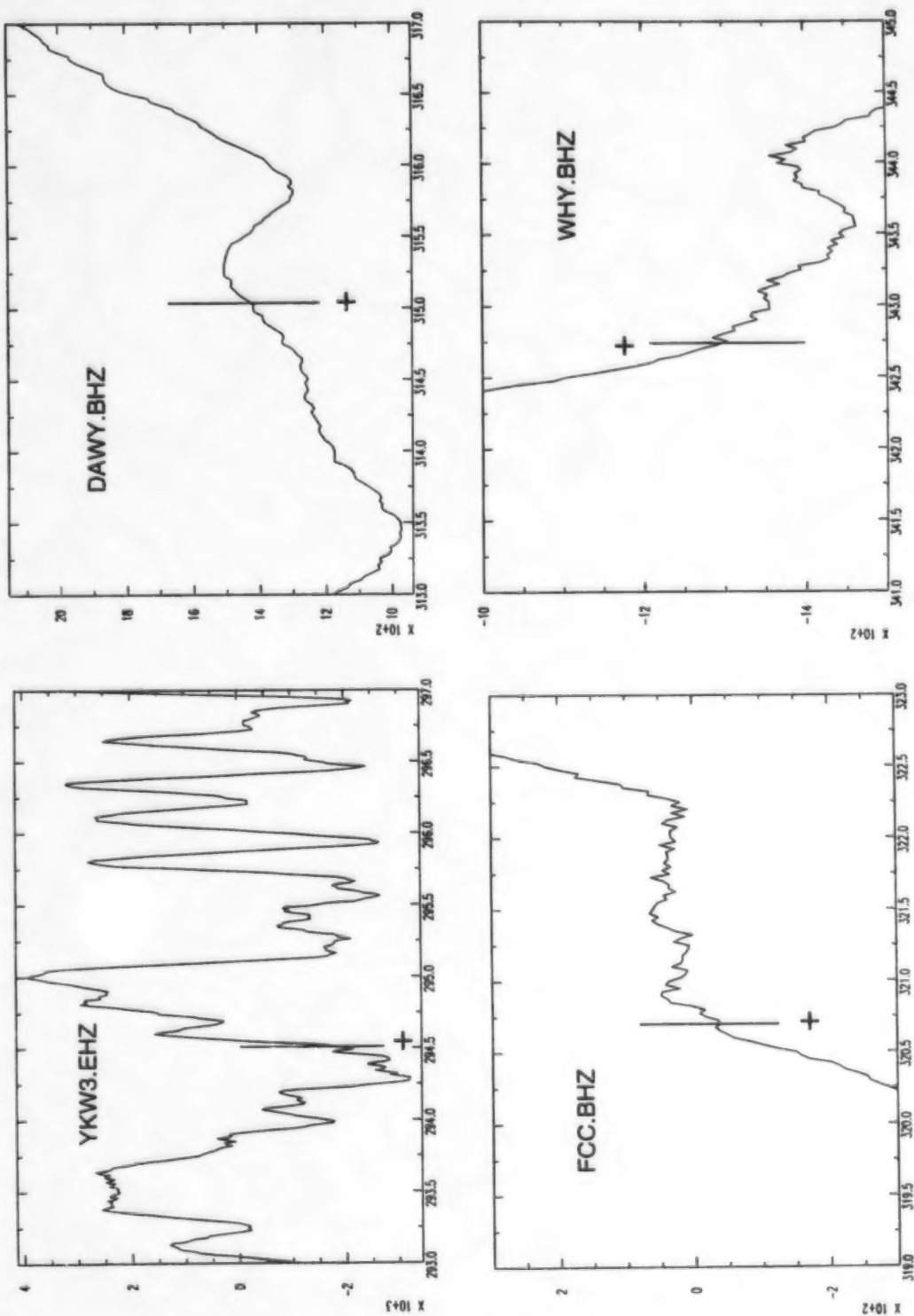


Figure 21b

Axel Heiberg Island, Northwest Territories: 22 December 1998

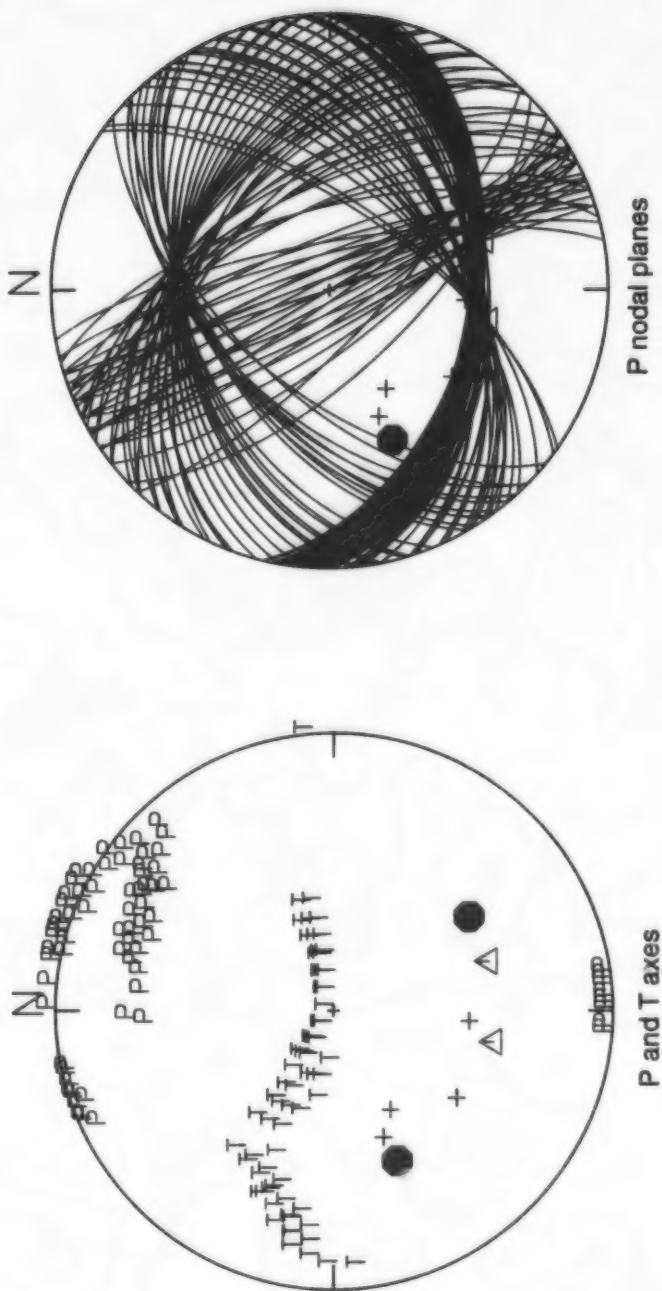


Figure 22

27 DECEMBER 1998: BAFFIN BAY

Seismic Zone: Baffin Bay
Latitude: 74.30° N
Longitude: 70.29° W
Depth: 18 km (fixed)
Magnitude: 4.2 (M_L)
Origin Time: 21:51:59 (UT)
Comments:

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
IGL	679	221.7	49.1	D
RES	732	285.1	49.1	D
ALE	931	7.2	49.1	D
FRB	1182	175.8	49.1	+

Focal Mechanism Solutions

total number solutions: 339
grid search: 10°
misfits: 0
comments: if FRB treated as impulsive and other stations given double weight, number of solutions is reduced to 232

Preferred solution: insufficient data to determine

Fault Plane:

Strike: undetermined
Dip: undetermined
Rake: undetermined

P-axis:

Trend: not in SE quadrant
Plunge: undetermined

T-axis:		
	Trend:	SE quadrant
	Plunge:	undetermined
B-axis:		
	Trend:	not in ESE octant
	Plunge:	undetermined

Figure Captions:

Figure 23. Seismograms from which polarity data were read by the authors.

Figure 24. Focal mechanism solutions. Lower hemisphere projection. The P and T axes are shown on the left and the P nodal planes on the right. Data are also plotted. Solid symbols indicate compressional first motions and open symbols dilatations. The bottom figure shows the data only.

Baffin Bay: 27 December 1998

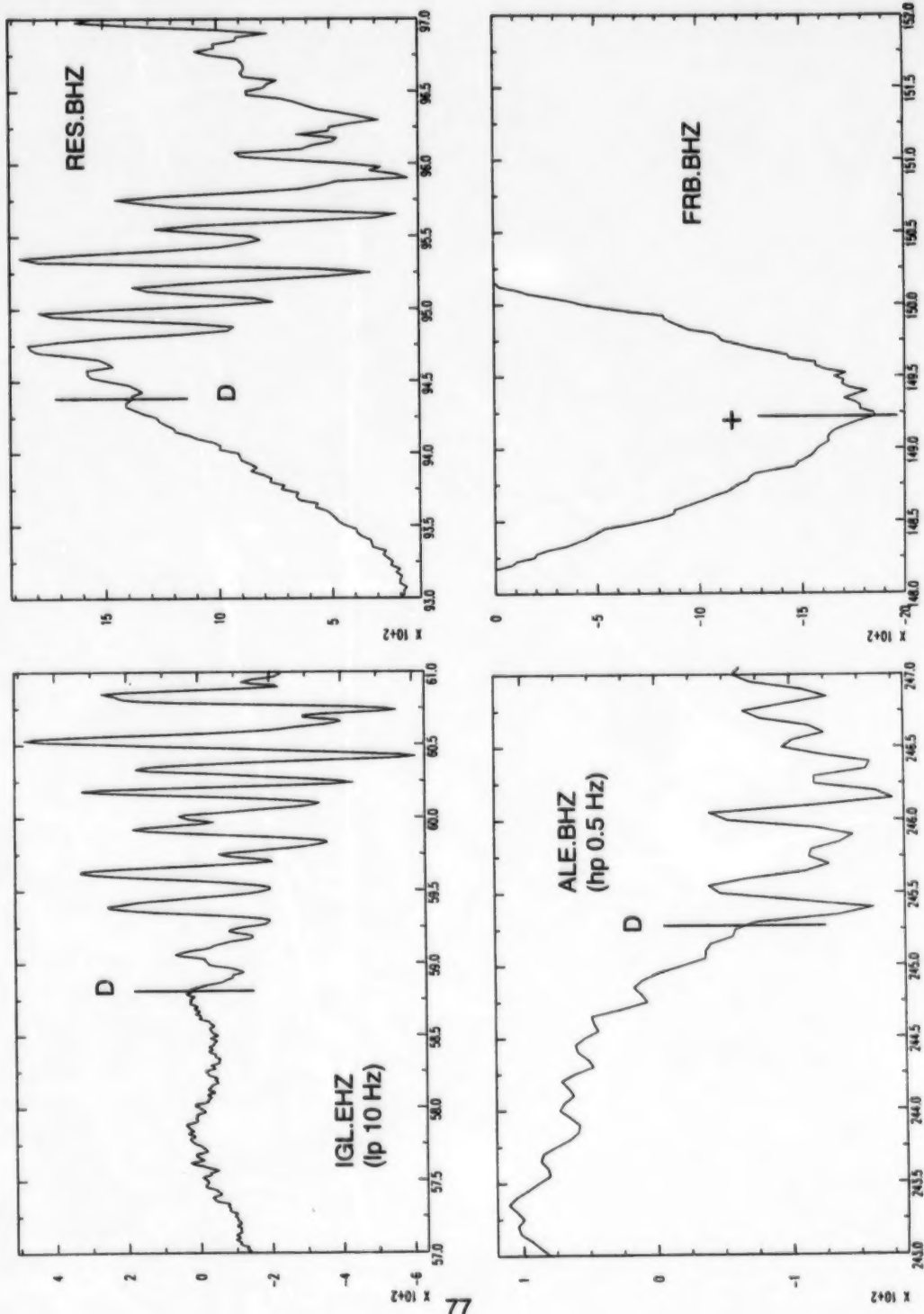


Figure 23

Baffin Bay: 27 December 1998

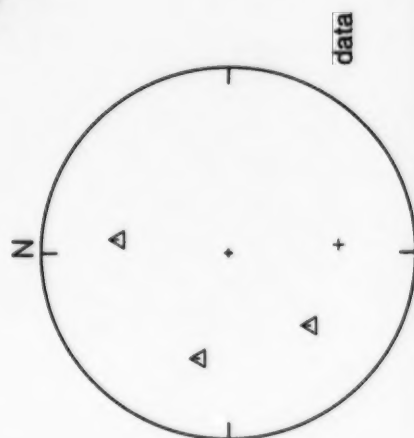
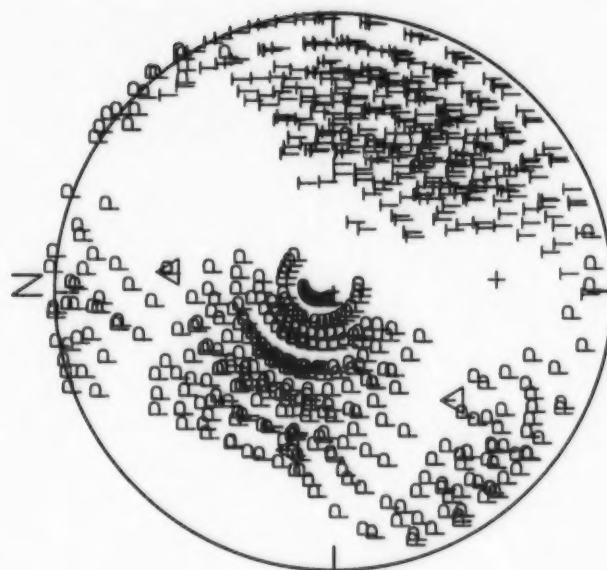


Figure 24

PREVIOUSLY PUBLISHED FOCAL MECHANISMS

No known published focal mechanisms exist for any earthquakes that meet our selection criteria. On 25 September 1998 an earthquake occurred in the Ohio-Pennsylvania border region. Because this earthquake was widely felt in southern Ontario, we include the focal mechanism for this earthquake in this paper. Readers interested in the data used to determine the solution should consult the reference cited.

25 SEPTEMBER 1998: OHIO-PENNSYLVANIA BORDER, USA

Latitude: 41.57° N
Longitude: 80.35° W
Depth: 5 km
Magnitude: 5.4 (m_N)
Origin Time: 19:52:56 (UT)
Comments: -although this event did not occur within Canadian territory, it is included because it was widely felt in southern Ontario

Focal Mechanism: strike: 303° (176°)
dip: 51° (53°)
rake: 51° (128°)

Reference: Harvard online CMT catalog; note that this solution was obtained by moment tensor inversion and not by analysis of first motions; to date we have not seen a published first motion solution for this earthquake

Comments: for completeness we include a table of polarities from CNSN stations for this earthquake and tabulate the possible focal mechanism solutions based solely on these data; note that we could not obtain a unique solution from CNSN data due to poor azimuthal coverage; of the three potential solutions two have similar fault plane orientations to the CMT solution but a higher component of thrust motion while the third is different in terms of orientation and sense of slip (oblique-normal); the first motion at LG4Q is inconsistent with all 3 solutions

Polarity Data

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
EFO	190	26.5	49.1	C
SADO	369	15.0	49.1	C
CRLO	551	24.7	49.1	C

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
WBO	561	45.5	49.1	D
OTT	566	39.8	49.1	C
EEO	573	9.8	49.1	C
GRQ	665	31.2	49.1	C
TRQ	696	40.0	49.1	-
MOQ	776	54.9	49.1	C
DPQ	830	44.3	49.1	+
KAPO	892	349.9	49.1	C
A11	1025	48.6	49.1	D
A54	1025	47.0	49.1	+
LMQ	1036	47.0	49.1	D
TBO	1060	321.0	49.1	C
A64	1080	46.4	49.1	D
A21	1084	47.5	49.1	D
CNQ	1268	45.0	49.1	D
LG4Q	1419	17.1	49.1	D
SMQ	1427	43.0	49.1	-
ULM	1538	314.1	48.6	C
SCHQ	1778	29.4	46.6	C
DRLN	1971	56.6	43.9	-
FCC	2140	338.0	40.8	C
EDM	2760	309.2	31.8	C
PNT	3151	299.4	29.8	C
PMB	3401	301.8	29.8	C
PGC	3433	298.1	29.7	C

Station	Distance (km)	Azimuth (°)	Take-off Angle (°)	First Motion
DLBC	3906	315.9	28.9	C
INK	4294	331.6	28.1	C
HYT	4347	319.3	28.0	C
DAWY	4469	324.3	27.7	C

Focal Mechanism Solutions

Strike	Dip	Rake
118.47	50.73	77.04
317.89	41.03	74.66
251.62	69.30	-40.89

total number solutions: 3
 grid search: 5°
 # misfits: 1
 comments: misfit at LG4Q; cannot constrain focal mechanism from CNSN data alone; use CMT solution (above) as preferred

Figure 25: Map showing epicenter and CMT focal mechanism for the Pennsylvania-Ohio earthquake. The 3 smaller and lighter colored mechanisms show the solutions based on CNSN first motion data only.

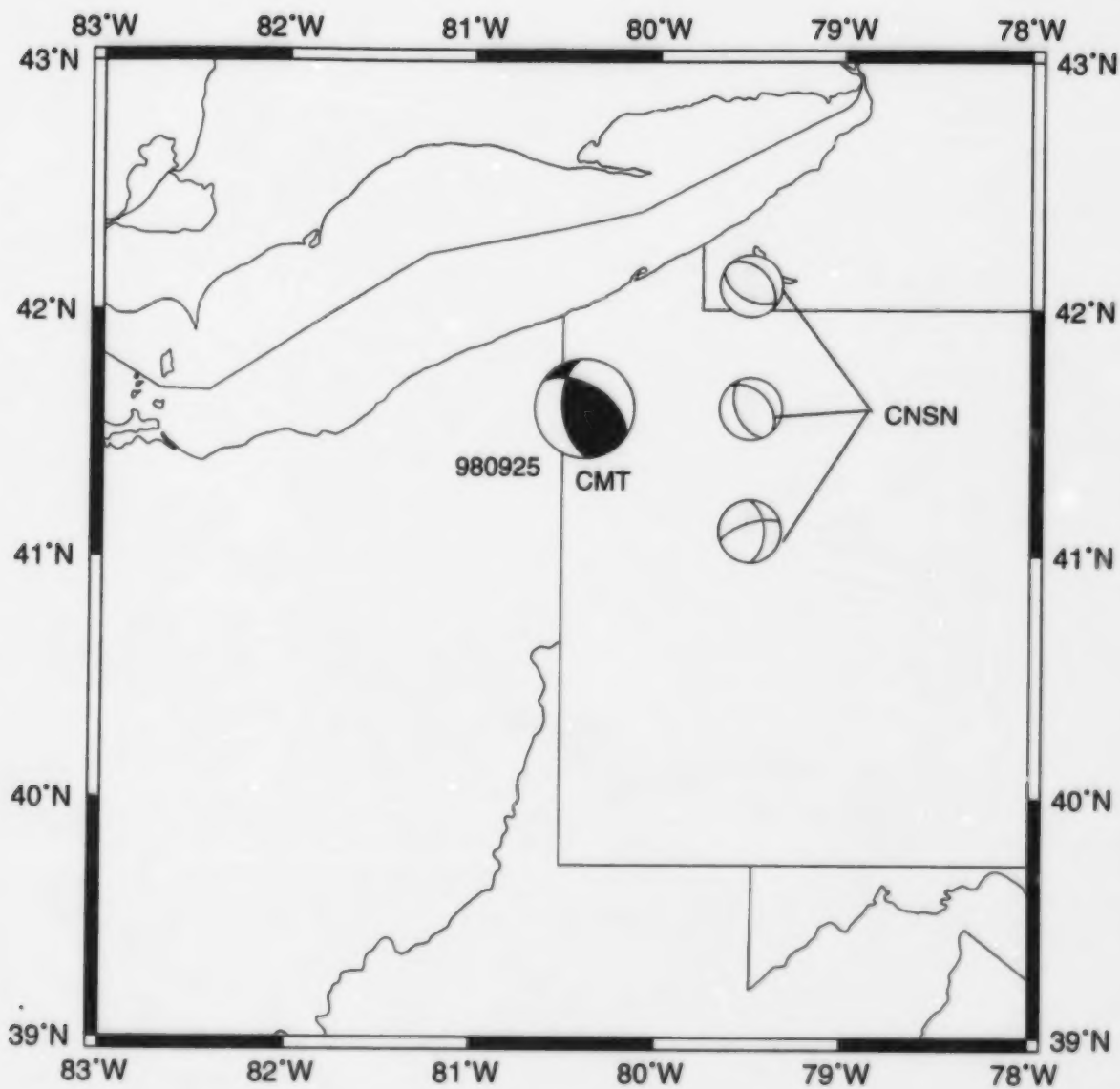


Figure 25

DISCUSSION

Southeastern Mainland: This was the only region for which we were consistently able to obtain well constrained fault plane solutions (Figure 26). As is the case for most New Brunswick earthquakes (Choy *et al.*, 1983; Wetmiller *et al.*, 1984; Adams *et al.*, 1988, 1989) event 980715 is a predominantly thrust faulting event. Its roughly northwest-southeast strike differs from the most common strike direction, near north-south, for this region, but the northeast-southwest trending P-axis is typical of eastern Canada (Adams and Basham, 1991; Zoback, 1992). 980730 occurred in the western Quebec seismic zone. The predominantly thrust mechanism is typical of earthquakes in this region. The NNW striking nodal plane is rotated slightly from the NW striking nodal planes more commonly found for earthquakes in this seismic zone (Wahlström, 1987; Adams *et al.*, 1988, 1989; Adams, 1991; Bent 1996a,b; Bent and Perry, 1999) but is within the range of variation observed. The focal mechanism for 981022, which occurred in the Lower St. Lawrence seismic zone, indicates predominantly thrust motion on a plane striking parallel to the St. Lawrence River. The few existing mechanisms for earthquakes in the Lower St. Lawrence seismic zone show some variation in faulting type and orientation, but the majority have a large thrust component of motion and at least one nodal plane roughly parallel to the St. Lawrence River (Adams *et al.*, 1988, 1989).

Laurentian Slope: Two selected events (980908 and 981013) occurred in this region, where station coverage is very poor. No conclusions can be made regarding either the focal mechanism or stress axes orientations for 980908. Conclusions regarding 981013 rely heavily on emergent data and should be used with caution. A pure normal faulting mechanism for 981013 can be ruled out. The P-axis is in the southeast quadrant with a shallow to moderate plunge; the T-axis is either close to southwest or is in the ENE octant; the B-axis has a shallow to moderate plunge with a trend in the range from WSW to NE.

Labrador Sea to Baffin Bay: Two selected events occurred in the region: one in the Labrador Sea (981128) and one in Baffin Bay (981227). We were unable to determine focal mechanisms for either of these events. We note that Bent and Perry (1999) also had difficulties determining focal mechanisms for earthquakes in this region due to poor station coverage. Conclusions regarding stress axes orientations for 981128 rely heavily on emergent data and should be used with caution. The P-axis is in either the SSE or NNW octant, the T-axis is in either the northeast quadrant or WSW octant and the B-axis is in the western hemisphere. Stress axes orientations for 981227 are less dependent on emergent data but are very poorly constrained. The T-axis is in the southeast quadrant. The P-axis is not in the southeast quadrant and the B-axis is not in the ESE octant.

Boothia-Ungava: We were unable to determine a focal mechanism for the lone earthquake in this region (980930) although we are able to rule out a normal faulting mechanism. Despite the fact that the nearest available station (RES) was nearly 900 km

from the epicenter, azimuthal coverage was relatively good. Possibly the solution would have been better constrained if data from IGL and/or FCC had been available. The P- and B-axes orientations (south-southwest and southwest-northwest respectively) are consistent with the focal mechanism of an event near Wager Bay (971206 of Bent and Perry, 1999) which had a near north-south P-axis and a near east-west B-axis. The T-axis orientations differ: approximately northeast for 980930 and near east-west for 971206.

Far North: Focal mechanisms could be determined for neither of the events (981123 and 981222) from this region, both of which had epicenters on Axel Heiberg Island. The few constraints that could be placed on the stress axes suggest that the events are very different, but could also be an artifact of using (less reliable) emergent polarities in the calculations. 981123 has a near east-west trending P-axis and near north-south T-axis. The P-axis for 981222 is either in the quadrant from northwest to northeast or it is near north-south. The T-axis for this event is near east-west. There is more overlap in the B-axis orientations with the trend confined to the southwest quadrant for 981123 and the southern hemisphere for 981222. The closest event for which a focal mechanism is known to exist (980609 in Bent and Perry, 1999) has stress axes similar to those for 981123.

Figure 26. Focal mechanisms determined for earthquakes in southeastern Canada. Lower hemisphere projection with shaded regions representing compressional quadrants.

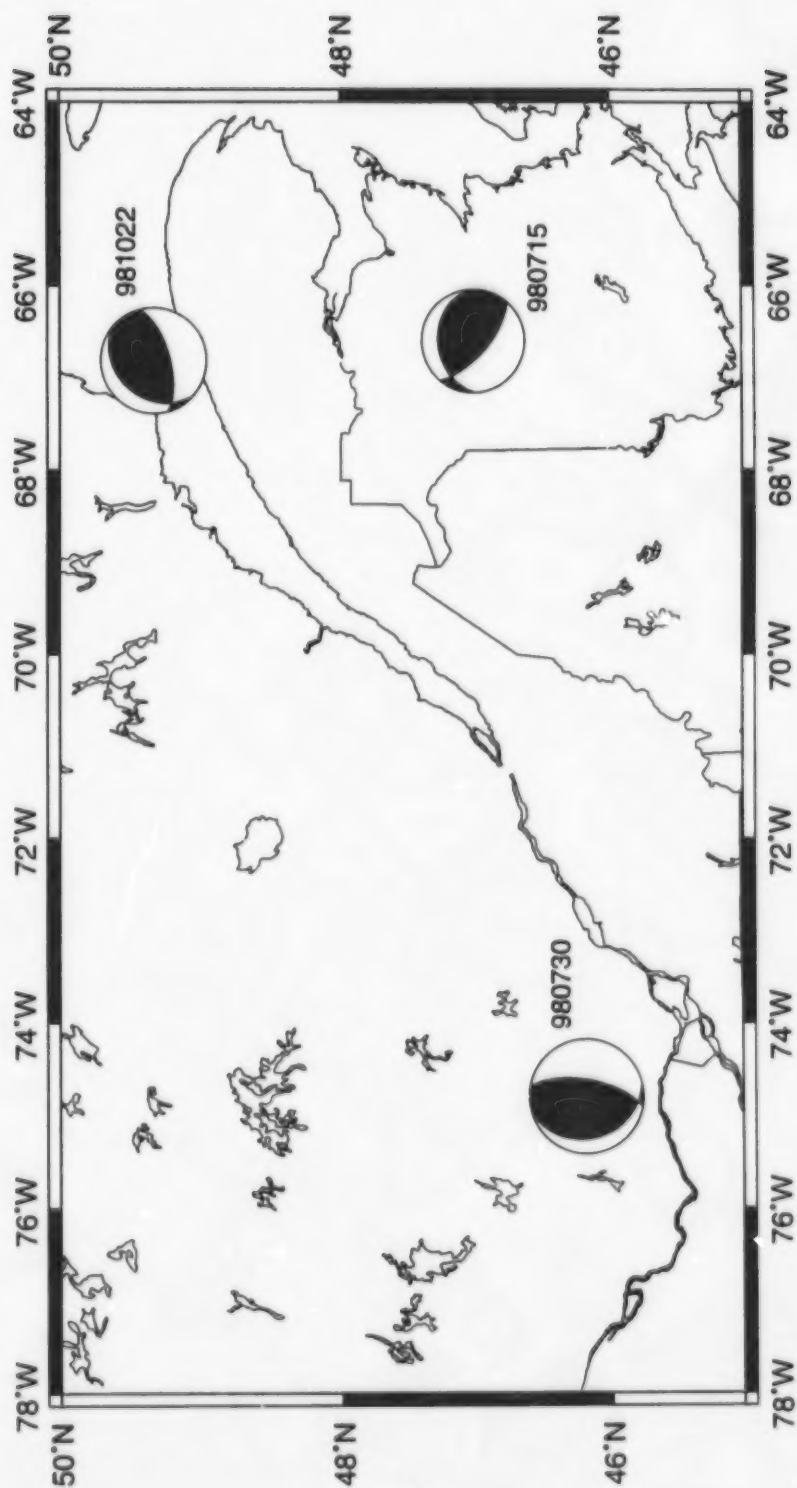


Figure 26

CONCLUSIONS

While the results of this study were somewhat disappointing in that we were able to determine focal mechanisms for only three of the ten selected earthquakes, we note that all of the events for which we could not obtain solutions occurred in the north or offshore where station coverage is known to be poor. We were, however, able to place some constraints on the stress axes or type of focal mechanism for all except one of these events. The difficulty in determining the focal mechanisms of northern and offshore events from first motion data underlies the need for a more powerful method of focal mechanism determination, such as a regional moment tensor inversion. This possibility is under investigation. Increased station density would make it easier to study northern and offshore events but we note that it would be difficult to greatly improve the azimuthal coverage in the offshore regions without (expensive) ocean-bottom seismometers. In southeastern Canada, where station coverage is good, we determined focal mechanism solutions for all three earthquakes, each of which occurred in a different seismic zone.

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TABLE 1
SUMMARY OF SOLUTIONS

Event	Plane 1			Plane 2			Type	Quality
	Strike(°)	Dip (°)	Rake (°)	Strike(°)	Dip (°)	Rake (°)		
980715	131	67	112	266	32	49	OT	B
980730	164	27	66	15	78	107	T	A
980908	??	??	??	??	??	??	??	N/A
980930	??	<60	??	??	<60	??	not N	N/A
981013	??	>40	??	??	>40	??	not N	N/A
981022	219	30	58	74	67	107	T	A
981123	??	40-60	??	??	40-60	??	??	N/A
981128	??	>40	??	??	>40	??	not N, T	N/A
981222	??	>40	??	??	>40	??	??	N/A
981227	??	??	??	??	??	??	??	N/A

* SS = strike-slip (rake within 30° of pure strike-slip)

T = thrust (rake within 30° of pure thrust)

N = normal (rake within 30° of pure normal)

O = oblique (rake more than 30° from end member; ON = oblique-normal; OT = oblique thrust)

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